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ORNL-4035
UC-70 — Waste Disposal and Processing

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CLINCH RIVER STUDY

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION • FOR THE U.S. ATOMIC ENERGY COMMISSION

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HEALTH PHYSICS DIVISION

COMPREHENSIVE REPORT OF THE CLINCH RIVER STUDY

Clinch River Study Steering Committee

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
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Contents

1. Summary

The Clinch River average flow at Clinch River mile (CRM) 20.8, the mouth of White Oak Creek, is about 4600 cfs. It had received releases of low-activity wastes for approximately 15 years, 1944 to 1959. This contaminated waste water resulted from operations at Oak Ridge National Laboratory, located on the White Oak Creek drainage basin; its discharge to the Clinch and Tennessee Rivers was carefully monitored during the 15-year interval. The average flow at Chickamauga Dam, Tennessee River mile (TRM) 471.0, about 118 river miles downstream from Oak Ridge, is approximately 37,000 cfs. Monitoring results have indicated that over 7000 curies of mixed fission products have been discharged to the river. This situation, in which low concentrations of radionuclides have been and were being released into a freshwater stream, afforded an excellent opportunity to study the chemical, physical, and biological dynamics of the system and to evaluate the safety of these river disposal operations on the basis of detailed observations and investigations which would not be practicable in a routine monitoring program.

Accordingly, a program of study was drawn up in 1959 and conducted over a period of five years, 1960 to 1964, which involved several federal agencies – the U.S. Atomic Energy Commission (USAEC, ex officio), the U.S. Geological Survey (USGS), the U.S. Public Health Service (USPHS), and the Tennessee Valley Authority (TVA); three state agencies – the Tennessee Department of Public Health (TDPH), the Tennessee Stream Pollution Control Board (TSPCB), and the Tennessee Game and Fish Commission (TGFC); and Oak Ridge National Laboratory, at which headquarters for the work program was provided in the Health Physics Division.

These agencies assumed the following prime responsibilities: hydrologic measurements and dispersion tests (USGS, TVA, and ORNL); water sampling (ORNL and TVA); water sample analysis [TSPCB (stable constituents), USPHS (radionuclides), and ORNL (supplemental analyses)]; bottom sediment sampling and analysis (USGS, USPHS, and ORNL); fish sampling and analysis (ORNL, USPHS, and TGFC); systems analysis [TVA, USGS, ORNL (mass balance), and Harvard Water Resources Group (computer simulation)]; and radiation safety analysis (ORNL, TDPH, TVA, USPHS, and USAEC). Most of the work by ORNL, USGS, USPHS, and the Harvard group was supported by the USAEC's Division of Reactor Development and Technology. Other agencies who contributed significantly to the program, namely, TVA, TSPCB, and TDPH, provided their own means of support. Approximately 60 scientists and engineers contributed to the total effort.

Radionuclides of primary importance in the study [based on quantities released, radioactive half-lives, and recommended MPC_w values (maximum permissible concentrations in water)] were

^{60}Co, ^{90}Sr, ^{106}Ru, and ^{137}Cs. The distribution, redistribution, and concentration of these radionuclides were determined by systematic collection and analysis of samples of water, bottom sediment, fish, and other aquatic organisms. Most environmental samples were analyzed for stable-chemical constituents as well. Additional knowledge of the dynamics of the river system was gained from hydrologic measurements, dispersion tests, laboratory experiments, and various computer programs.

PRINCIPAL CONCLUSIONS

Distribution of Radionuclides in River Water and Bottom Sediments

Results of the water sampling and analysis program indicated that ^{90}Sr, ^{60}Co, and ^{106}Ru in the waters of White Oak Creek, Clinch River, and the Tennessee River were associated principally with "dissolved" solids. This means that the radionuclides were either in solution or retained by very fine suspended particles. In marked contrast, most of the ^{137}Cs (69 to 92%) was associated with the larger size of suspended solids in White Oak Creek and Clinch River waters. In the Tennessee River, however, 70 to 80% of the ^{137}Cs was in solution or associated with very fine solids, that is, solids not removed by a high-speed centrifuge.

From information obtained by the analysis of cores taken from bottom sediments of the Clinch River, the variation of gross gamma radioactivity with depth essentially reflected the variations of ^{137}Cs concentration in the sediments. There were notable similarities in the annual releases of ^{137}Cs from White Oak Creek and the variations of ^{137}Cs with depth in the sediment of many cores. This suggests that the ^{137}Cs was deposited in the bottom sediments by the settling of suspended solids entering the river from White Oak Creek.

Radionuclide Transport and Accumulation Downstream

The distribution and redistribution of radionuclides in the Clinch-Tennessee Rivers downstream from Oak Ridge were investigated as a basis for estimating radiation doses that might be received by people using these rivers for water supply, fishing, and recreation. Of particular interest were the concentrations and mass movement of radionuclides in the water phase of the river environment; the accumulation of radionuclides in the rivers by sorption on the suspended sediments and sedimentation, and by cycling in the biota; and the effects of discharges from the new Melton Hill Dam.

Concerning movement in the water phase, sampling and analysis of water at selected stations downstream and measurements of flow at each station for a period of two years (November 1960 through November 1962) gave the total load of each radionuclide passing each station. The cumulative loads at each station were then plotted progressively with time to produce mass curves which would reveal losses or gains between successive downstream stations. The mass curves of ^{90}Sr and ^{106}Ru showed that virtually all the ^{90}Sr and ^{106}Ru entering the Clinch River passed through the river system in the water phase as far as Chattanooga, the last downstream station.

Mass curves of ^{60}Co showed a very slight loss of ^{60}Co in the Clinch during the first half of the sampling period; thereafter, the load going in at White Oak Dam arrived later, undiminished, at Chattanooga. Less confidence can be placed in the ^{137}Cs curves because of inaccuracies in analysis and malfunctioning of a sampler at Centers Ferry station on the Clinch, but they indicated a definite loss of ^{137}Cs in the lower reaches of the Clinch River (due to sedimentation) if allowances are made for known errors in sampling and analysis. For the two-year period of record, only at White Oak Dam station were the mean concentrations of these radionuclides higher than the appropriate MPC_w values for drinking water.

Estimated inventories of radioactivity in the Clinch River bottom sediments, based on the analysis of many cores, indicated an accumulation of approximately 200 curies, or only about 1.5% of the total radioactivity released from White Oak Creek to the river since 1944. In the downstream portions of the river (below CRM 12), sediment deposits and accumulations of radioactive sediments were distributed generally over the entire stream bed. In the upper and swifter-flowing reaches of the river, radioactive sediment had accumulated only along the sides of the stream channel.

The inventory of radionuclides accumulated in the Clinch River biomass could not be measured, but a method of estimating the maximum radioactivity incorporated in the biota was developed, based on the known volume of water and its phosphate content. The estimates showed that the maximum accumulation would constitute only an insignificant part of the total load of radioactive contaminants in the river. Thus the river system could be likened to a pipeline with little retention of the radioactive contaminants in either the bottom sediments or the biota.

Melton Hill Dam will alter the Clinch River flow regime considerably, since it will be used to help carry peak power loads for certain periods of each day (except on weekends), and intermittent flow releases may be as high as 18,000 cfs. These high flows will cause the level of water in the Clinch River to rise rapidly and thus to block the outflow of White Oak Creek water for about 6 hr each day. At the cessation of these power releases, the contaminated White Oak Creek water will flow out into the river and be flushed downstream with the next power release. To test the effect of these peaking flows on dispersion and dilution downstream, Rhodamine-B dye was added to the water flowing over White Oak Dam, and dispersion of the dye in White Oak Creek embayment and in the Clinch River was monitored under simulated summer and winter flows. The tests showed that the minimum dilution factors of White Oak Creek water in Clinch River water at CRM 14.4, the intake of the first water treatment plant downstream (Oak Ridge Gaseous Diffusion Plant), after a weekend of no releases from Melton Hill Dam (the most critical case) was 54 for summer conditions and 17 for winter conditions. Moreover, it was observed that the dispersion process due to the intermittent power releases was not greatly different from that for steady flow conditions, especially at sections of the river a few miles below the mouth of White Oak Creek. It was also shown that the concentrations of dye downstream could be predicted on the basis of a one-dimensional transport equation with eddy diffusion coefficients computed from previous steady-flow tracer tests.

Biological Aspects

Biological investigations sought to determine the uptake and turnover of radionuclides in the biota and the effects of ionizing radiation on aquatic organisms. They were concerned principally with studies of the fish populations and bottom organisms.

Among the fish, the white crappie was selected for intensive study because a fish-tagging survey had shown that it did not migrate far in the river and, therefore, that its exposure to radioactive releases could be estimated more closely. The biological half-lives of radiostrontium in fish flesh and bones were investigated, because this information would permit calculations of the rate at which ^{90}Sr concentrations in fish tissues would respond to changing environmental concentrations of ^{90}Sr. Using ^{85}Sr and whole-body counting techniques, no significant loss of strontium from the bone was detected; but the biological half-life of strontium in the flesh of white crappie was found consistently to be less than 1 hr.

In addition to the white crappie, clams were studied as indicator organisms for estimating the uptake and turnover of radionuclides in biota. River clams are relatively immobile on the river bottom, and the ^{90}Sr content of their shells should be representative of the river water at particular locations. The clam studies showed that the concentration of ^{90}Sr in clamshells was directly proportional to the concentration of ^{90}Sr in river water to which the clams were exposed.

The effects of radiation on aquatic organisms were studied by examination of the salivary gland chromosomes of *Chironomus tentans* larvae in an effort to detect chromosomal aberrations which might be attributed to radiation exposures. Such induced aberrations were observed, but it appeared that they were eliminated from the *Chironomus* population by natural selection. Therefore it was concluded that no permanent radiation damage to the population of this organism would occur.

Radiation Safety Aspects

The evaluation of radiation safety required estimates of dose to downstream population groups who might be exposed by (1) drinking contaminated water; (2) eating contaminated fish; (3) swimming, skiing, or fishing in contaminated water; (4) consuming plant or animal foodstuffs grown on plots irrigated with contaminated water; and (5) close proximity to contaminated sediments on the river bottom, on river banks, or in a water treatment plant. The twofold purpose of this evaluation was to develop a generalized method of safety analysis that might have application elsewhere, and to establish, as factually as possible, conservative estimates of radiation dose which downstream users of the Clinch-Tennessee Rivers might have received because of exposure to radioactive materials in the rivers.

Results of the analyses showed that ^{90}Sr and ^{137}Cs were the critical radionuclides contributing most heavily to radiation doses, and that drinking water and eating fish were the critical exposure pathways. Considering intakes via these pathways, the total doses to the critical age groups residing on the Clinch River and the Tennessee River (18-year-old and 14-year-old respectively) were estimated to be 3.2 and 0.45 rems respectively. In both situations the dose estimate was less than one-tenth of the maximum permissible dose recommended by the National Council on Radiation Protection and Measurement (NCRP) and the International Commission on Radiological Protection (ICRP).

Long-Term Monitoring

One of the objectives of the Clinch River Study was to consider appropriate long-term monitoring procedures applicable to the river system. In general, it was concluded that the safety analysis had shown ingestion of water and fish to be the principal pathways of potential radiation exposure. This suggests that the monitoring and proportional sampling of water should be continued at the point of release, and also downstream in the river. The frequency of sampling and the methods of monitoring should be adjustable and should be reviewed and improved from time to time as found necessary by the Laboratory. The long-term monitoring program should include collection and analysis of selected species of both game and commercial food fish as frequently as might be considered necessary.

Monitoring for radionuclides in bottom sediments of the river should be continued to some extent as long as radioactive releases can be shown to have a significant influence on the radioactivity of bottom deposits. However, the monitoring of bottom sediments is of a lower order of importance than monitoring of water and fish.

Biota other than fish need not be sampled, since water sampling and analysis for suspended and dissolved constituents should detect significant changes in the radionuclide content of organic detritus and similar materials. At the same time the monitoring groups should be alert to special needs and problems of monitoring, and should conduct studies or special monitoring as necessary to define actual and probable future conditions of radiation exposure from use of the rivers. The adequacy of monitoring programs should be examined from time to time, and monitoring procedures should be revised and improved accordingly.

Also, for evaluation of potential exposures from ingestion of water and food, continuing information about the types and quantities of radionuclides discharged to the river and their distribution and concentrations in the river system should be maintained. This would require further investigations of any extreme or anomalous conditions that might be detected in the course of routine monitoring surveys.

Appraisal of the Clinch River Study

The scope of the Clinch River Study was broad, and its objectives included both general and specific aims. One aspect of particular interest may be the organization and the conduct of the study.

One strong point of the study was that it was based on a long-term plan which was developed before the beginning of the investigation and revised from time to time during the period of study. The conjunction of six major technical and professional agencies in the study, with substantial contributions from each, helped greatly to assure its success. The study was organized so as to provide coordination of the work of the different agencies without conflicting with their basic policies and interests. With general guidelines and policies of the study determined by a steering committee which included representatives of all the participating agencies, remarkable cooperation and unanimity of viewpoints were achieved; a variety of abilities and special skills were brought to bear on many of the problems encountered. It was especially helpful to be able to take full advantage of the backlog of available information on prevailing conditions in the river, such as stream flow, sediment accumulations, and radionuclide discharges.

Some weaknesses in the study were noted, particularly the lack of adequate cross checks of analytical work by the different analytical laboratories participating in the study. Also, the press of time and the volume of work prevented adequate detailed investigations to explain the behavior of radionuclides in the river and to elucidate the basic mechanisms involved. Other difficulties, such as delays in the preparation of analytical equipment and computer programs and failure to start early in the collection of data for some of the long-term measurements that are needed, caused the final results to be somewhat less than might have been attained.

2. Introduction

HISTORICAL BACKGROUND

The effects of past releases of radioactive materials to the Clinch River environment are more or less cumulative and have an influence upon present conditions. Therefore, a brief review of the development of the Oak Ridge National Laboratory in relation to the problems of waste management and disposal is pertinent in this report of the Clinch River Study.

Oak Ridge National Laboratory (then known as the Clinton Laboratories) was established in 1943 under the wartime Manhattan Engineer District as a temporary pilot plant for the atomic energy works to be constructed at Richland, Washington. The graphite reactor, a chemical separations pilot plant ("Hot Pilot Plant"), and radiochemical laboratories for analyses and research were constructed. A number of large underground concrete tanks (about 10^6 gal total capacity) were installed for storage of all the radioactive chemical and uranium wastes that would accumulate during the life of the Laboratory, which was then expected to be about one year. However, continuation of the Laboratory and expansion of its program in 1943 and later years increased the volume of liquid wastes beyond the capacity of the tanks. This necessitated means for waste disposal to supplement the tank storage system.[1,2]

The original policy of the Manhattan Engineer District and the specific requirements of the Atomic Energy Act of 1946 and its later amendments, which established the U.S. Atomic Energy Commission (AEC), have demanded safety against excessive radiation exposure of occupational workers and members of the general public in the nuclear energy program.

For the disposal of radioactive liquid wastes there are two generally recognized alternatives: (1) dilute the radioactive materials to nonhazardous concentrations while dispersing the wastes into the environment; or (2) separate and concentrate the radioactive components of the waste and store them indefinitely, or at least until they have been rendered nonhazardous by radioactive decay.

Waste management philosophy at ORNL during the period 1943 to 1950 was to dilute and disperse the large volumes of low-activity liquid wastes within the safe disposal capacity of the

[1] F. N. Browder, *Radioactive Waste Management at Oak Ridge National Laboratory*, ORNL-2601 (Apr. 14, 1959).

[2] Y. Feige, F. L. Parker, and E. G. Struxness, *Analysis of Waste Disposal Practice and Control at ORNL*, ORNL-CF-60-8-72 (Oct. 4, 1960).

Clinch and Tennessee Rivers and to concentrate and store the higher-activity wastes for which dilution and dispersion were not practicable. The purpose was to contain most of the radioactive constituents and by this means to minimize the quantities of radioactivity released to the environment.

From about 1950 to the beginning of the Clinch River Study in 1960 there was further expansion of the Laboratory program and a consequent increase in quantities of wastes produced at ORNL. This caused greater emphasis to be placed on waste treatment for removal of most of the radionuclides and upon methods for disposal of the partially decontaminated liquids. Various waste treatment and disposal processes were employed from time to time in this effort. These included: construction of a settling basin in the ORNL area and construction of White Oak Dam on White Oak Creek, thus creating the impoundage known as White Oak Lake (1943–44); dosage of liquids in the waste storage tanks with caustic to promote settling and retention of radionuclides in the bottom sludge (begun in 1943); evaporation of intermediate-activity wastes (1949–54); ground disposal of intermediate-activity wastes by seepage into the Conasauga shale underlying Melton Valley, first in open pits and later in covered seepage trenches (from 1952 to the present); and lime-soda treatment for precipitation of radionuclides in low-activity waste water (1958). Concurrently, monitoring facilities were added to the waste collection system in the ORNL area by which the various types of liquid wastes could be measured, sampled, and separated into different classes according to the concentrations of radionuclides in the liquids. By use of these facilities more reliable surveillance and control of discharges of waste water to the Clinch River were provided.

THE CLINCH RIVER PROBLEM

After the first few months of operation of the Laboratory and the later expansion of its program it was apparent that excess waste water and some radioactive liquid wastes would, of necessity, have to be released to the Clinch River through White Oak Creek. It was recognized that such releases involved potential human radiation exposures and would have to be controlled so as to minimize or avoid health hazards to people living downstream. The primary problem was to determine what limits of discharge were acceptably safe.

The radioactive liquid wastes produced by the expanded Laboratory operations were classified by Browder according to these levels of radioactivity:[1] (1) highly active radioactive liquid chemical wastes; (2) highly active liquid uranium wastes; and (3) large-volume, mildly contaminated process waste water. The most highly active chemical and uranium wastes at ORNL actually were of only "intermediate" activity levels (0.1 to 0.5 curie/gal) and were usually so designated in Laboratory reports. The liquid uranium wastes were later reprocessed to remove and recover the usable uranium, leaving only two classes, namely, chemical wastes and contaminated process waste water. Of these the more radioactive chemical wastes were collected in stainless steel monitoring tanks, then were jetted or pumped through underground pipes to the waste storage tanks, and finally, after precipitation and settling, were decanted for further treatment or disposal. Since 1952 disposal of the decanted waste has been by seepage into the Conasauga shale. The contaminated waste water was treated in the lime-soda treatment plant and then monitored and discharged to White Oak Creek.

After the seepage pit method of ground disposal was put into use, there were three choices for disposition of liquid wastes at the Laboratory: (1) storage in waste tanks and retention for radioactive decay, (2) fixation in the soil (using seepage pits or trenches), and (3) discharge through White Oak Creek to the Clinch River. Fortunately, all discharges from ORNL to the Clinch River were through White Oak Creek, and a continuous proportional sampling and monitoring station at White Oak Dam provided a good control point for assessment of the radionuclide releases to the river.

Near the end of 1959, when the Clinch River Study was organized, there were several uncertainties regarding contamination of the Clinch River. Even though all radioactive discharges to the river passed through White Oak Dam and could be monitored at that location, there was only general knowledge of the numerous sources of radioactive wastes that entered White Oak Creek, the compositions and quantities of waste released from ORNL were highly variable, and methods for reducing contamination of the river were not then available. Without such knowledge the Laboratory's Operations Division was uncertain of the degree or methods of reduction of waste discharges that should be attempted, and the Health Physics Division was handicapped in its role of recommending limits of discharge that should be observed and maintained.

During conduct of the Clinch River Study, sampling surveys were made to locate and define additional sources of radioactive contamination in White Oak Creek (see Chap. 3). It was found that although the process waste water discharged to the creek was monitored, there were unknown and important waste releases which were reflected in the overall measurements at White Oak Dam that had not been evaluated individually. These included: discharges of cooling water and other effluents from reactors; effluents from water-filled storage "canals" for irradiated fuel elements; minor discharges from various sources such as the clothing decontamination laundry, the sanitary-sewage treatment plant, and equipment decontamination facilities; seepage from the waste pits, which might find its way through the earth into nearby watercourses; and elution and re-solution into the ground water of radioactivity that had accumulated in the bottom sediment of White Oak Lake.

Since establishment of the Laboratory, the primary emphasis in routine monitoring of releases to the Clinch River had been to assure that the concentrations of radioactive materials in the river were below the maximum permissible concentrations for drinking water (MPC_w) recommended by ICRP and the NCRP (National Committee on Radiation Protection and Measurements and now the National Council on Radiation Protection and Measurement). This is apparent in the limits of discharge at the boundaries of the ORNL reservation reported by Parker,[3] in

[3]H. M. Parker, *Review of Water Monitoring Procedures at Clinton Laboratories*, MDDC-401 (July 1944; declassified 1946).

bottom sediment surveys in the Clinch and Tennessee Rivers by the Health Physics Division as reported by Cottrell,[4] and in the safety analysis of radionuclide releases to the river by Cowser and Snyder.[5] As indicated above there were various needs for more detailed surveys and research studies to evaluate the many sources of radioactive effluents and to investigate the factors that influence the behavior of radionuclides after discharge to the river. Such extensive research could not be attempted by the Applied Health Physics Section, whose program was authorized primarily as a monitoring service. In 1959 a number of workers at ORNL assembled available information about downstream conditions on which knowledge was deficient and which needed to be defined by a study of the Clinch River. It was from this exploratory inquiry that a proposal and plan for the Clinch River Study were developed.[6]

ELEMENTS OF THE CLINCH RIVER STUDY

Objectives

The purpose of the study of the Clinch River downstream from ORNL was to obtain fundamental information on the physical, chemical, and biological dynamics of this freshwater stream, which for nearly 20 years had received releases of low-level radioactive wastes. It was believed that information from such a broadly conceived study would have important applications for two world-wide problems involving large-scale environmental contamination: First, what is the overall diluent capacity of freshwater environments for the continuous input of large volumes of low-level radioactive waste water? Second, what is the long-term impact of radioactive contamination on such an environment?[6]

As a framework for the organization and execution of the Clinch River Study five general objectives were adopted: (1) determine the fate of radioactive materials currently being discharged to the Clinch River; (2) develop an understanding of the mechanisms of dispersion of radionuclides released to the river; (3) evaluate the radiation safety of current disposal practices in the river; (4) evaluate the limitations of this river for receiving radioactive effluents safely; and (5) suggest long-term monitoring procedures.

Organization

A draft of the proposed plan for the Clinch River Study was submitted on November 9, 1959, to various agencies expected to be involved in the study.[6] At the invitation of the U.S. Atomic Energy Commission (AEC), representatives of two Tennessee state agencies and three other federal agencies met with representatives of the AEC and ORNL on December 18, 1959. The

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[4] W. D. Cottrell, *Radioactivity in Silt of the Clinch and Tennessee Rivers*, ORNL-2847 (Nov. 18, 1959).

[5] K. E. Cowser and W. S. Snyder, *Safety Analysis of Radionuclide Release to Clinch River*, ORNL-3721, Suppl. 3 (in preparation).

[6] Prepared by F. L. Parker *et al.*, *Plan for Clinch River Study*, 23 pp. (Multilith), Nov. 9, 1959.

purpose of the meeting was to explore the need for and scope of the proposed river study and to determine the extent to which these agencies could participate. Representatives of the ORNL Health Physics Division gave detailed reports of waste releases to the river and of the river monitoring program. Representatives at the meeting reached a general decision that the study should be undertaken, and the several agencies were asked to suggest what their respective roles in this cooperative project would be.[7,8]

Steering Committee and Subcommittees. – The Clinch River Study Steering Committee was organized, consisting of one member from each agency that agreed to participate actively and three ex officio members from the AEC. Organization of the Steering Committee included a representative from each of the following: ORNL Health Physics Division, Tennessee Game and Fish Commission, Tennessee Department of Public Health and Tennessee Stream Pollution Control Board (one representative), U.S. Geological Survey, U.S. Public Health Service, Tennessee Valley Authority, AEC Headquarters, Division of Reactor Development (ex officio), AEC Headquarters, Division of Biology and Medicine (ex officio), and AEC Oak Ridge Operations (ex officio).

E. G. Struxness, of the ORNL Health Physics Division, was elected chairman of the Steering Committee and served in that capacity throughout the five-year study. Since the initial organization of the Steering Committee the agencies represented have remained the same, although the persons representing particular agencies have been changed from time to time. The membership and actions of the Steering Committee throughout the period of study have been recorded in the six status reports, issued as ORNL documents.[8–13]

From the beginning it was understood that the Steering Committee would be responsible for general plans and policies, including the technical adequacy of the study procedures adopted and executed in the work program, and releases of the information obtained. Technical aspects of the study in specialized fields were assigned by the committee to four subcommittees, namely, Water Sampling and Analysis, Bottom Sediment Sampling and Analysis, Aquatic Biology, and Safety Evaluation.[10,11] The subcommittees formulated program plans and provided liaison between the work groups of the participating agencies and the Steering Committee. Each subcommittee was also responsible for progress reports to the Steering Committee covering results in its own field.

The Steering Committee held regular meetings approximately twice a year, with an open meeting for progress reports and an executive session for committee actions. Special meetings

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[7] Minutes of Meeting on "Plan for Clinch River Study," Oak Ridge National Laboratory, December 18, 1959 (Multilith).

[8] R. J. Morton (ed.) *et al.*, *Status Report No. 1 on Clinch River Study*, Clinch River Study Steering Committee, ORNL-3119 (July 27, 1961).

[9] *Ibid.*, No. 2, ORNL-3202 (Mar. 30, 1962).

[10] *Ibid.*, No. 3, ORNL-3370 (Nov. 21, 1962).

[11] *Ibid.*, No. 4, ORNL-3409 (Sept. 11, 1963).

[12] *Ibid.*, No. 5, ORNL-3721 (October 1965).

[13] *Ibid.*, No. 6, ORNL-3941 (in preparation).

were held when necessary. During the five-year period from January 1960 to December 1964, the Committee held nine open meetings, nine executive neetings, and three special meetings.

Participating Agencies. — The study was carried out as a cooperative research project in the Health Physics Division of the Oak Ridge National Laboratory. Its administration was centered in the Radioactive Waste Disposal Research Section of the Division with joint participation by the Ecology, Internal Dose, and Applied Health Physics Sections. Other agencies, including USGS, TVA, USPHS, and TGFC, participated by assigning workers to the field and laboratory programs. In addition the Tennessee Department of Public Health and the Robert A. Taft Sanitary Engineering Center of the USPHS in Cincinnati analyzed water samples for stable chemical and radionuclide determinations respectively. The ORNL Analytical Chemistry Division provided a variety of specialized analytical services.

Related programs included the AEC-supported river survey programs by the USPHS in Cincinnati, the routine monitoring program of the ORNL Applied Health Physics Section, and the continuing studies of aquatic biology by the ORNL Ecology Section. Insofar as possible the participating agencies oriented their regular programs so that the information obtained for other purposes could be used to augment the Clinch River Study.

The allocation of responsibility for sample collection and analysis by the various agencies was summarized in the appendix of Status Report No. 1.[8] In a late stage of the study F. L. Parker, Chief of the ORNL Radioactive Waste Disposal Research Section, was designated by the Steering Committee as Study Coordinator in order to provide more direct supervision of the work program.

BASIC SCHEME OF STUDY

Requirements for Understanding Dynamics of the Disposal-River System

The first two objectives, dealing with the fate of radionuclides and mechanisms of dispersion, required an understanding of these aspects of the disposal-river system: (1) the hydrology of the streams (particularly that of the Clinch River arm of Watts Bar Reservoir); (2) the chemistry of the river system (qualitative and quantitative analyses of water, suspended solids, and bottom sediments for the major chemical constituents and trace elements of interest); (3) the biology of the streams (occurrence and habits of important aquatic organisms); (4) the distribution and redistribution of radionuclides in physical components of the river environment; and (5) the uptake and retention of radionuclides in aquatic organisms. To attempt a mass balance analysis required systematic measurements or estimations of radionuclide inputs, loads, and losses in each major component of the system, that is, water, biota, and sediments.

Data required for the analysis included: (1) measurements of flow in White Oak Creek and at selected sampling stations upstream and downstream on the Clinch-Tennessee Rivers; (2) measurements of radionuclide concentrations in water, suspended solids, and bottom sediments throughout the study reach; (3) measurements of the concentrations of stable chemicals in environmental samples taken throughout the study reach; (4) measurements of radionuclide concentrations in tissues of important aquatic organisms; (5) experimental measurements of the sorptive properties of suspended solids and bottom sediment constituents; and (6) experimental measurements of the uptake and retention of radionuclides by various aquatic species.

Requirements for Safety Evaluation

Perhaps the most important objective, and the one which had the greatest influence on the study as a whole, was that of evaluating radiation safety. Indeed, it may be said that the primary justification for the study was to obtain information which would allow a more exact and reliable assessment of potential radiation exposures. The evaluation of radiation safety, as related either to continual discharges of radioactive materials or to accidental intermittent releases, involves an understanding of the occurrence of radionuclides in water and bottom sediments, of the types and concentrations of radionuclides present in water and aquatic foodstuffs at various locations in the river system, and of the uses to which the rivers are put for water supply, fishing, and recreation. As the study proceeded it was evident that all of the five stated objectives[10] were closely related to radiation safety.

The data required for adequate safety evaluation included: (1) identification of the important radionuclides from the standpoint of potential human exposure; (2) identification of the principal exposure pathways from radioactivity in the river system; (3) identification of the most important potentially exposed population groups; and (4) measurements or estimates of the concentrations of radionuclides in the various exposure media from which to estimate radiation doses.

3. Clinch and Tennessee River Basins

The field investigations of the Clinch River Study were confined, primarily, to the Clinch River downstream from the mouth of White Oak Creek and to the Tennessee River from the Clinch River to Guntersville Dam (Fig. 3.1).

GEOGRAPHY

Nuclear Facilities

Oak Ridge National Laboratory is 7 miles south of the city of Oak Ridge, Tennessee (1960 population 27,169) and about 30 miles west of Knoxville, Tennessee. At ORNL the U.S. Atomic Energy Commission sponsors broad programs of research and development of nuclear power and

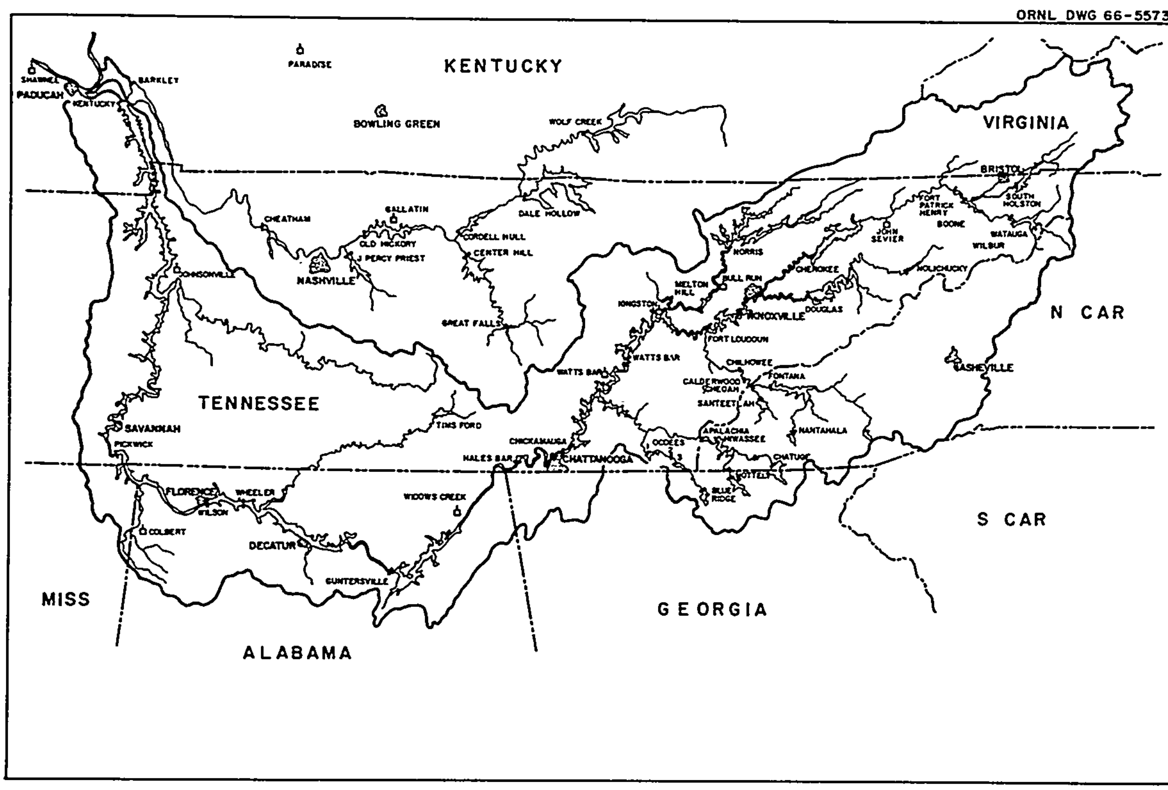

Fig. 3.1. Tennessee River Valley and Vicinity Showing Important Dams and Steam Plants.

power reactor technology. Most of the facilities at ORNL are within the White Oak Creek basin. Other facilities also operated in the Oak Ridge area for USAEC by Union Carbide Corporation are the Oak Ridge Gaseous Diffusion Plant (ORGDP) and the Y-12 Plant (Fig. 3.2). Some activities of ORNL are also located at ORGDP and Y-12.

Surface Features

The topography of the area, which is in the Valley and Ridge province, is characterized by a series of nearly parallel valleys and ridges which trend northeast.

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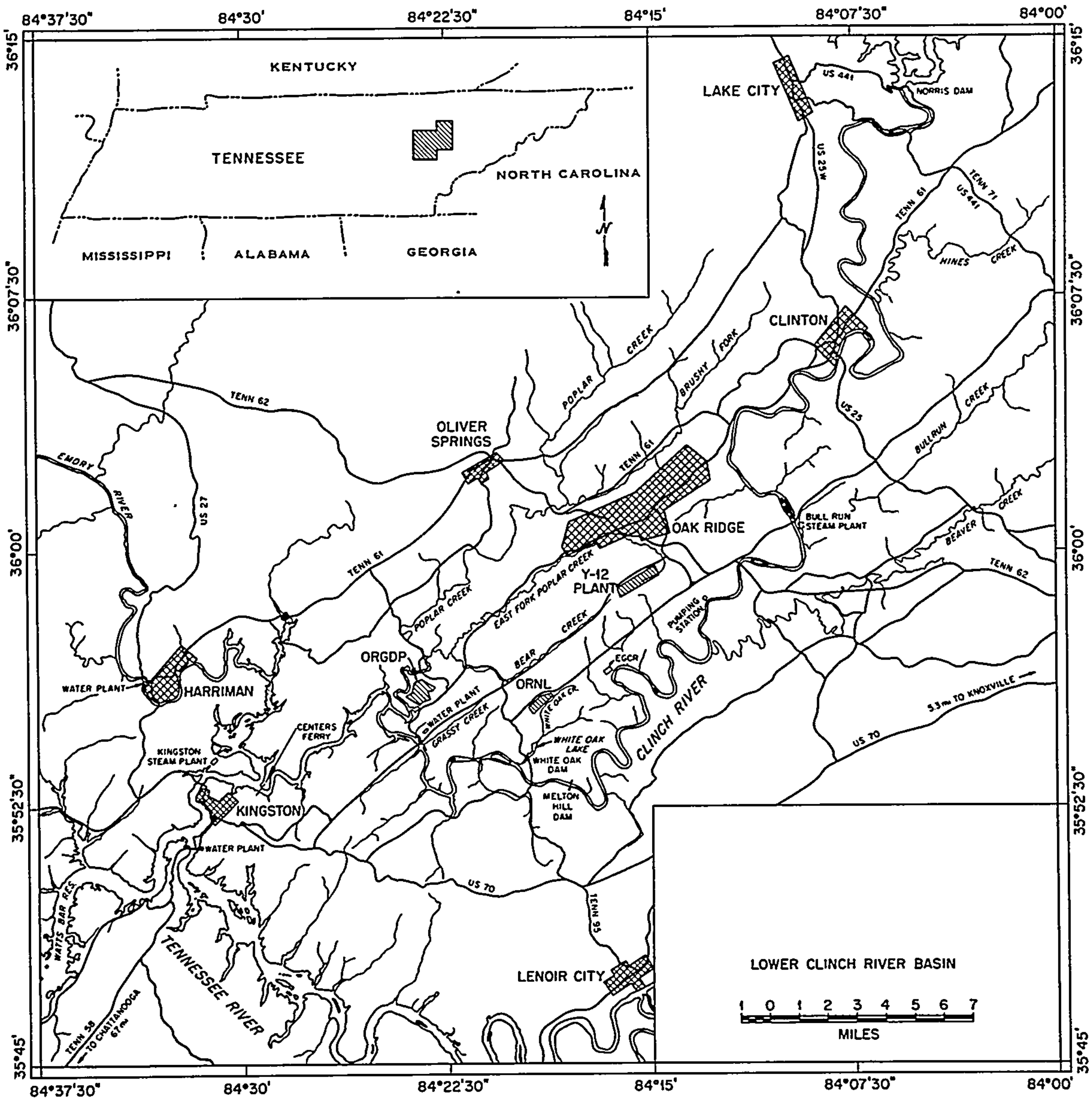

Fig. 3.2. Oak Ridge and Vicinity Showing Location of USAEC Nuclear Facilities.

The parallel valleys and ridges reflect the geologic structure of the region. The strata are southeast-dipping and consist of alternating units of dolomite, shale, sandstone, and limestone. The formation of the valleys and ridges is the result of the varying resistances of the strata to weathering and erosion.[1] The soils overlying these strata are mostly residuum. Only in areas immediately adjacent to the larger streams are there alluvial soils.

The crests and slopes of the ridges are heavily wooded, most of the cover being deciduous trees. An estimate has been made that nearly two-thirds of the USAEC reservation in Oak Ridge is wooded. Towns, farmlands, industries, and reservoirs occupy open lands in the valleys.

Climate

East Tennessee has moderate temperatures and a humid climate. The mean annual precipitation at the U.S. Weather Bureau station in Oak Ridge is 54.7 in. (1948–63). Most of the precipitation is rain; light snows occur infrequently from November through March. Some seasonal variations in precipitation occur, the precipitation being greatest from December through March.

The mean annual temperature is 58.3°F. The coldest months are January through March, with mean monthly minimum temperatures near freezing. The warmest period of the year is June through August; the mean monthly temperature for these months is slightly greater than 85°F.[2]

CLINCH RIVER BASIN

The headwaters of the Clinch River are in southwestern Virginia. From here the river flows southwest to its mouth at Kingston, Tennessee (drainage area, 4413 square miles) (Fig. 3.1). Tributaries of the river important to this report are White Oak Creek, Poplar Creek, and Emory River. The mouths of these tributaries are at Clinch River miles (CRM) 20.8, 12.0, and 4.4 respectively.

Streamflow Records

Between 1936 and 1964, gaging stations were operated on the Clinch River in the vicinity of White Oak Creek, and streamflow records for these stations have been published by the Geological Survey. These records were published as "Clinch River near Wheat," September 1936 to January 1941 (CRM 14.5, drainage area 3385 square miles); "Clinch River near Scarboro," February 1941 to September 1962 (CRM 39.0, drainage area 3300 square miles); and "Clinch River at Melton Hill Dam," October 1962 to September 1964 (CRM 23.1, drainage area 3343 square miles). Based on these records, the maximum, mean, and minimum flows of the Clinch River at the mouth of White Oak Creek (CRM 20.8) are about 43,000, 4600, and 0 cfs respectively.

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[1] W. M. McMaster, *Geologic Map of the Oak Ridge Reservation*, ORNL-TM-713 (Nov. 22, 1963).

[2] *Local Climatological Data with Comparative Data, 1963, Oak Ridge, Tenn.*, U.S. Weather Bureau, Feb. 14, 1964.

Tributary Inflows[a]

Stream	Average Flow (cfs)	Period of Records (years)	Drainage Area (square miles)
White Oak Creek at White Oak Dam	13.5	5	6.01
Poplar Creek near Oak Ridge	167	4	82.5
Emory River near Oakdale	1419	37	764

[a]*Surface Water Records of Tennessee, 1963*, U.S. Geological Survey, Chattanooga, Tenn., 1963.

Regulation

Early in the study, flows in the river were affected mainly by control operations at Norris Dam, by water level fluctuations in Watts Bar Reservoir, and by outflows from Watts Bar Dam. Daily fluctuations in the flow due to peak-power hydroelectric generation, such as shown in Fig. 3.3, occurred through the year. In the winter months a few consecutive days of high sustained flows (~20,000 cfs or higher) would occur because of flood-control operations. After the filling of Melton Hill Lake in May 1962, flows in the study reach were affected by spillway gate operations at the new dam.

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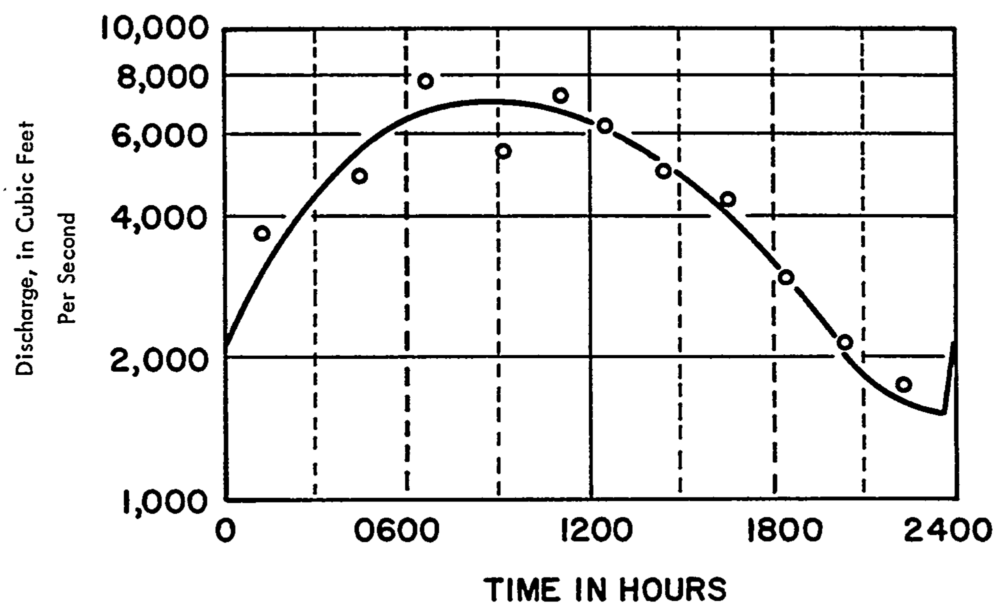

Fig. 3.3. Typical Variation in Flow of the Clinch River During a Day in the Vicinity of White Oak Creek Due to Power Releases from Norris Reservoir.

From late spring to early fall the nominal water levels in the lower Clinch River up to CRM 28 (in the backwater of Watts Bar Lake) are about 6 ft higher (elevation 741) than during the remainder of the year (elevation 735).

Melton Hill Dam, a multipurpose structure for navigation and peaking hydroelectric operation, began power operations in the summer of 1964. In full operation (after December 1964), the power releases from Melton Hill Lake vary in a pattern similar to those in Fig. 3.4.

In the early plans for the study it was realized that construction of Melton Hill Dam would have important effects on flow velocities, temperatures, and sediment transport in the Clinch River. It was estimated that temperatures of the Clinch water at the mouth of White Oak Creek would be about 5°F lower than before construction of the dam, and that the nutrient-rich White

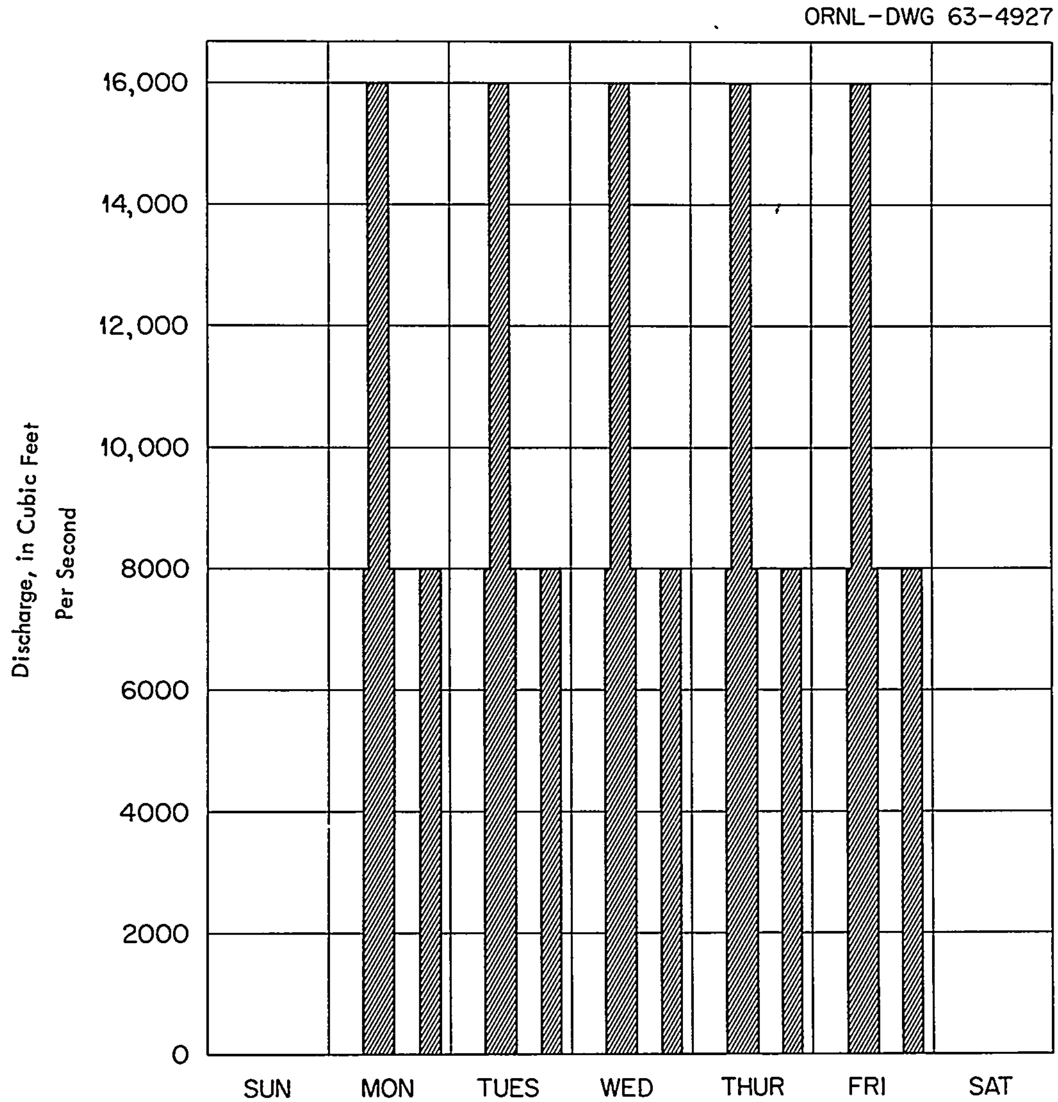

Fig. 3.4. Estimated Summer Discharge Patterns of Melton Hill Dam.

Oak Creek waters would float on the surface of the river when Melton Hill was not releasing water.

A brief period of investigation was available after Melton Hill Dam was completed, and several observations and tests of the changed conditions were made. These included studies of dispersion, water elevations, dilution factors, concentrations and variations of contaminants discharged from White Oak Creek to the river, and the various hydraulic parameters that affected river conditions.

Stratification

Waters released through the hydroelectric plants at Norris or Melton Hill Dam are cold, being drawn from the lower levels of the reservoirs. These cold waters underflow warm water of Watts Bar embayment in the summer, resulting in thermal stratification. The beginning of stratification centered around CRM 9.5 when flows were regulated by Norris Lake.[3] The releases from Melton Hill Lake begin to stratify flow much farther downstream, below the Emory River or perhaps into the Tennessee River. When the power plant at Melton Hill Dam shuts down, stratification is reestablished throughout the lower Clinch River quite rapidly.[4]

Diluent Capacity

Flows in the Clinch River have provided adequate dilution of the radioactive waters flowing from White Oak Creek, that is, below the permissible concentrations recommended by NCRP.[5] Average and median dilutions have been found to be 670 and 570 times greater, respectively, than flows in the creek.[6] A seasonal variation in dilution exists, and dilution is normally greater from August through December (Fig. 3.5).

Diffusion

Several tracer tests have been conducted to determine (1) where the waters from White Oak Creek became completely mixed with those of the Clinch River, (2) the rate of movement of these waters in the river, and (3) the effects of turbulent diffusion on the movement of radionuclides. Full mixing, vertically and transversely, occurs within 4 to 6 miles downstream from the mouth

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[3] R. J. Morton (ed.), *Status Report No. 5 on Clinch River Study, Clinch River Study Steering Committee*, ORNL-3721 (October 1965).

[4] F. L. Parker, "Movement of Radionuclides in the Clinch River," *Proc. of the Third Annual Sanitary Engineering Conference*, Nashville, Tennessee, May 25, 1965.

[5] K. Z. Morgan, "Statement of K. Z. Morgan, Director of the Health Physics Division, Oak Ridge National Laboratory," *Industrial Radioactive Waste Disposal, Hearings Before Special Subcommittee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States (86th Congress)*, vol. 1, pp. 428–45, U.S. Government Printing Office, Washington, 1959.

[6] P. H. Carrigan, Jr., "Dilution of Low-Level Radioactive Waste Waters by Waters of Clinch River," *U.S. Geol. Survey Bulletin, 1965* (in manuscript).

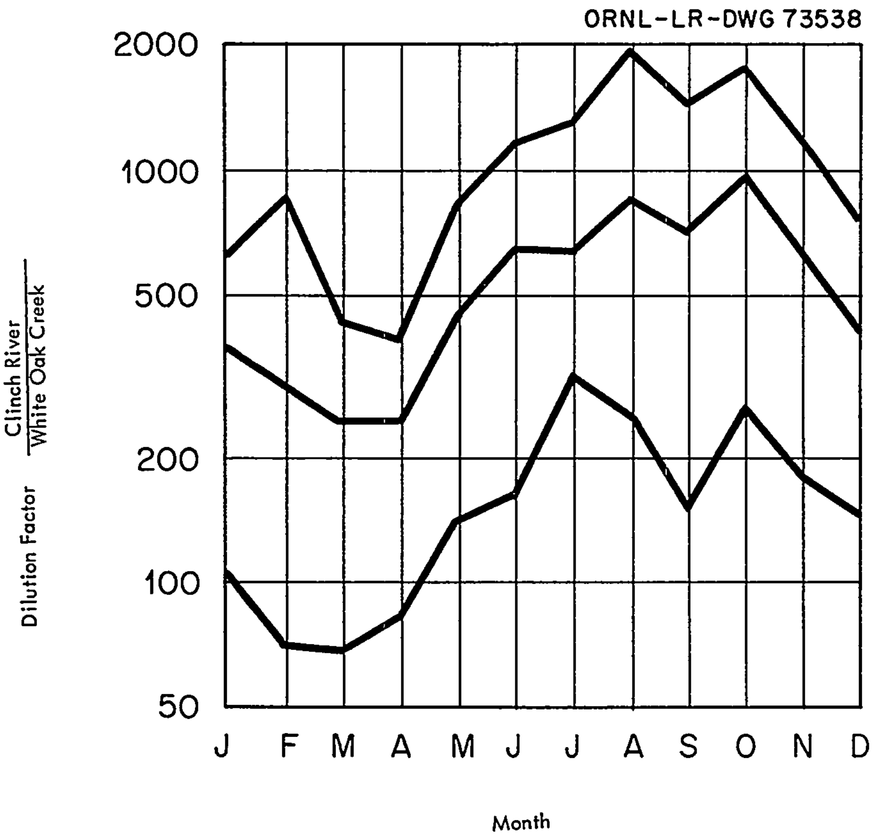

Fig. 3.5. Maximum, Mean, and Minimum Monthly Dilution Factors, 1951–60.[8]

of the creek.[7–9] Full mixing is achieved upstream from the first point of withdrawal for water supply, the ORGDP water plant intake. Analytical methods for predicting the rate of movement, verified by field tests, have been found to be accurate.[10] Transverse and vertical diffusion reduce radionuclide concentrations greatly in the first 4 to 6 miles of movement downstream from the mouth of White Oak Creek. The reduction in concentration except by dilution, once lateral mixing is complete, is very small.[7,8]

Sediment Deposition

Downstream from CRM 14, appreciable deposition of sediments on the bed of the Clinch River begins. The volume of sediment deposition generally increases towards the mouth of the river,

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[7]R. J. Morton (ed.), *Status Report No. 3 on Clinch River Study, Clinch River Study Steering Committee*, ORNL-3370 (Nov. 21, 1962).

[8]R. J. Morton (ed.), *Status Report No. 4 on Clinch River Study, Clinch River Study Steering Committee*, ORNL-3409 (September 1963).

[9]E. G. Struxness, "Radioactive Waste Disposal Research and Engineering," *Health Phys. Div. Ann. Progr. Rept. July 31, 1959*, ORNL-2806.

[10]A. J. Cooper, P. H. Carrigan, Jr., and B. J. Frederick, "Determination of Time of Water Travel," *U.S. Geol. Survey Report, 1966* (in preparation).

with deposition extending laterally over wider and wider parts of the bed. Upstream from CRM 14, deposition is confined to parts of the channel immediately adjacent to the banks.[11]

Changes in the sediment deposition patterns are influenced by the effects of water impoundment in Watts Bar embayment and on sediment transport capacity. The flow area of the embayment increases in the downstream direction; as a consequence, the sediment transport capacity of the river decreases.

TENNESSEE RIVER BASIN

The contaminated waters of White Oak Creek flow from the Clinch River into the Tennessee River at Kingston, Tennessee, Tennessee River mile (TRM) 567.7 (Fig. 3.1).

The Tennessee River is highly regulated, with several multipurpose reservoirs from Knoxville, Tennessee, to Paducah, Kentucky. These reservoirs are for flood control, navigation, electric-power generation, and recreation. The data on location and drainage area at each dam and on bottom sediment accumulation in each reservoir are listed in Table 3.1.

[11] P. H. Carrigan, Jr., and R. J. Pickering, *Radioactive Materials in Bottom Sediment of Clinch and Tennessee Rivers: Distribution and Vertical Distribution of Radionuclides in Undisturbed Cores*, Progress Report, Part B of Subcommittee on Bottom Sediment Sampling and Analysis, ORNL-3721, Suppl. 2B (in press).

Table 3.1. Location and Drainage Area of Dams on Tennessee River and Accumulated Sediment Deposits in Their Reservoirs

Dam	Mile (TRM)[a]	Drainage Area[a] (square miles)	Sediment Volume[b] (acre-ft)	Accumulation Period[b,c] (years)
Fort Loudon	602.3	9,550		
Watts Bar	529.9	17,310	22,082[d]	15.2
Chickamauga	471.0	20,790	7,781[e]	21.1
Hales Bar	431.1	21,790	–519[f]	25.7
Guntersville	349.0	24,450	33,153	20.6
Wheeler	274.9	29,590	71,697	24.8
Wilson	259.4	30,750	46,372	32.6
Pickwick Landing	206.7	32,820	25,057	23.6
Kentucky	22.4	40,200	88,694	15.1

[a] *Drainage Areas for Streams in Tennessee River Basin*, Rept. No. 0-5829, Hydraulics Data Branch, Div. of Water Control Planning, TVA, May 1958.

[b] Data furnished by TVA.

[c] Period ending in summer 1961.

[d] Excluding sediments in Tennessee River embayment upstream from mouth of Clinch River and in embayments of Piney and Emory Rivers and of White Creek.

[e] Excluding sediments in tributaries.

[f] (–) Indicates scour.

The long-term mean annual flows at principal streamflow stations on the Tennessee River for the period of record ending September 30, 1960 (from records of the Tennessee Valley Authority and U.S. Geological Survey), are as follows:

Streamflow Station	Mile (TRM)	Mean Annual Flow (cfs)	Period of Record (years)
Knoxville, Tenn.	651.4	12,810	61
Chattanooga, Tenn.	476.6	37,030	86
Florence, Ala.	259.4	50,620	66
Paducah, Ky.	21.6	63,790	71

WATER USE

Waters in the Clinch and Tennessee Rivers are used for water supply, industrial processes, fishing and recreation, irrigation, generation of electric power, and navigation.

Drinking Water Supplies

Morton[12] has listed 12 water supplies serving an estimated population of 200,000 within 170 river miles of White Oak Creek that may use water containing minor amounts of radionuclides released from ORNL. Principal users are the Oak Ridge Gaseous Diffusion Plant on the Clinch River and the communities of Soddy-Daisy, Falling, Wallens Ridge, Chattanooga, and South Pittsburg, Tennessee, on the Tennessee River. Also, stratified conditions in the rivers during the summer months create a remote possibility that Clinch River waters may flow upstream under the warmer surface waters in tributaries to water intakes at Harriman, Kingston, and Spring City, Tennessee.

Industrial Applications

The major industrial use of river water is for cooling purposes. At the present time such uses occur at ORGDP and the Kingston Steam Plant. The supply for ORGDP is withdrawn at CRM 14.4 (Fig. 3.2). Cooling water has been withdrawn at the ORGDP Steam Plant (now dismantled), CRM 13.2, and at Watts Bar Steam Plant (now in standby status), TRM 529.2 (Fig. 3.1). Waters of the Clinch River are deliberately diverted at CRM 4.4 to the cooling water intakes for the Kingston Steam Plant at mile 1.8 on the Emory River.[13]

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[12]R. J. Morton (ed.), *Status Report No. 1 on Clinch River Study, Clinch River Study Steering Committee,* ORNL-3119 (July 27, 1961).

[13]R. A. Elder and G. B. Dougherty, "Thermal Density Underflow Diversion," Kingston Steam Plant, *J. Hydraulics Div., Am. Soc. Civil Engr.* HY2, 84.

Potable and industrial water supplies for Oak Ridge, ORNL, and Y-12 are withdrawn from the Clinch River at CRM 41.5 and for Clinton at CRM 66.

Fisheries

Fish in study reaches of the Clinch and Tennessee Rivers are a typical warm water assemblage. Major fish groups include Centrarchidae (sunfishes, basses, and crappies), Catostomidae (suckers), and Ictaluridae (catfishes). Other than carp, the Cyprinidae (minnows) are poorly represented. Absence of small minnows may be attributed to lack of suitable habitat. Forage for piscivorous fish is provided by large populations of Clupeidae (threadfin shad, gizzard shad). In addition to these groups, sauger and white bass are two carnivorous fish regularly caught.

The fisheries resources of the Tennessee River system are used for their commercial value as well as for sport. Nongame fish, such as carp and buffalo, are commercially harvested for human consumption. Quantities and kinds of fish harvested from the Tennessee River and their dollar values are listed in Table 3.2.

Table 3.2. Commercial Fish Harvest,[a] Tennessee River

Calendar Year[b]	Paddlefish (lb)	Catfish (lb)	Drum (lb)	Carp (lb)	Buffalo (lb)	Carpsucker and Other[c] (lb)	Total (lb)	Value[d] (dollars)
	$\times 10^3$	$\times 10^3$	$\times 10^3$	$\times 10^3$	$\times 10^3$	$\times 10^3$	$\times 10^3$	$\times 10^3$
1946	131	688	44	103	172	7	1145	224
1947	100	628	55	104	180	7	1073	255
1948	100	774	63	138	266	5	1345	347
1949	103	804	68	186	306	8	1474	354
1950	90	848	106	157	239	6	1446	440
1951	81	934	92	189	399	3	1699	458
1952	108	1191	99	212	430	14	2053	494
1953	80	1148	126	242	337	11	1944	434
1954	68	1197	138	231	653	12	2298	468
1955	48	1166	114	156	375	12	1870	410
1956	81	1300	125	221	617	17	2362	475
1957	171	2017	112	577	1310	16	4203	807
1958	227	2238	157	486	1560	12	4680	913
1959	333	2973	195	689	1716	10	5916	1069
1960	272	2592	172	584	1229	3	4852	906
1961	458	2595	110	635	1450	2	5249	915
1962	216	2717	110	932	1481	156	5612	915
1963	496	5224	210	155	2014	433	8532	1585

[a]From Tennessee Valley Authority, Division of Forest Development, Norris, Tennessee, Annual Report 1964.

[b]Data through 1956 for Guntersville, Wheeler, Wilson, and Pickwick reservoirs only; data through 1962 based on records of major fish buyers, subsequently, on sampling of licensed commercial fishermen.

[c]Includes sturgeon, gar, suckers, and turtles.

[d]Amount received by commercial fishermen; retail value about twice as great.

Recreation

The recreational value of sport fishing is, in many ways, intangible. However, prior to construction of Melton Hill Dam there was little fishing on the Clinch River in the vicinity of White Oak Creek because of its general inaccessibility. With the closing of the dam, desirable tailwater sport fishing developed and access sites were constructed. Increased sport fishing in the Clinch River may be expected.

The Clinch (downstream from CRM 4), Emory, and Tennessee River embayments of Watts Bar Lake are favored areas for water skiing and some swimming. Local populations and tourists also engage in these recreational activities in the vicinity of Watts Bar Dam and in Chickamauga Lake near Chickamauga Dam.

Flood Control, Navigation, and Power Generation

Operation of the TVA multipurpose dams for flood control, navigation, and power generation results in regulated flow in the Clinch and Tennessee Rivers. When the threat of winter floods ends, water levels in the reservoirs are raised to increase power generation capacity. During warm periods of the year thermal stratification occurs in these reservoirs. Navigation locks are in all dams on the Tennessee River and in Melton Hill Dam.

Power releases cause pulsations in river flow (Fig. 3.4) and, as a result, surges in releases from White Oak Creek. The pulsations from Norris Lake releases were attenuated considerably downstream, which diminished the pulsations of releases from White Oak Creek. Power releases from Melton Hill Dam are not attenuated significantly between the dam and the mouth of White Oak Creek. Alternating and intermittent flows in the river and from the creek will result from these power operations. Thus, discrete masses of waste water will be released from the creek and be moved downstream as a body.[3]

Irrigation

Supplemental irrigation of agricultural crops and of pastures is increasing in the Tennessee River basin. In 1958 about 1000 farms in the basin were estimated to be using supplemental irrigation.[14] Ten years earlier about 100 farms were using irrigation.[3]

Waste Disposal

Sanitary, industrial, and radioactive wastes are released to the Clinch River. The municipal sewage effluents of Clinton and Kingston, Tennessee, are released directly to the river from treatment plants. Releases from other communities and USAEC facilities at Oak Ridge are into

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[14] K. E. Cowser and W. S. Snyder, *Safety Analysis of Radionuclide Release to the Clinch River*, ORNL-3721, Suppl. 3 (May 1966).

tributaries of the Clinch River. Detectable quantities of radioactive materials are released only from ORNL.

Wastes from many communities and industries are released into receiving streams tributary to the Tennessee River or directly into the river. No significant quantities of radioactive materials are known to be in these wastes.[14]

RELEASE OF CONTAMINATED WASTE WATER TO CLINCH RIVER

Fluctuations in the annual loads of radionuclides released to the Clinch River (Table 3.3) reflect changes in generation and in methods of waste treatment and disposal of radioactive liquids at ORNL.

The generation of radioactive liquid wastes at ORNL began in 1943. At that time the graphite reactor began operation and the extraction of plutonium and fission products from fuel elements was begun. After 1945 further developmental work in fission product extraction from irradiated reactor fuel was undertaken at the Laboratory. This work increased the generation of waste products.

Table 3.3. Yearly Discharges of Radionuclides to Clinch River (Curies)[a]

Year	Gross Beta	^{137}Cs	^{106}Ru	^{90}Sr	TRE (–Ce)[b]	^{144}Ce	^{95}Zr	^{95}Nb	^{131}I	^{60}Co
1944	600									
1945	500									
1946	900									
1947	200									
1948	494									
1949	718	77	110	150	77	18	180	22	77	
1950	191	19	23	38	30		15	42	19	
1951	101	20	18	29	11		4.5	2.2	18	
1952	214	9.9	15	72	26	23	19	18	20	
1953	304	6.4	26	130	110	6.7	7.6	3.6	2.1	
1954	384	22	11	140	160	24	14	9.2	3.5	
1955	437	63	31	93	150	85	5.2	5.7	7.0	6.6
1956	582	170	29	100	140	59	12	15	3.5	46
1957	397	89	60	83	110	13	23	7.1	1.2	4.8
1958	544	55	42	150	240	30	6.0	6.0	8.2	8.7
1959	937	76	520	60	94	48	27	30	0.5	77
1960	2190	31	1900	28	48	27	38	45	5.3	72
1961	2230	15	2000	22	24	4.2	20	70	3.7	31
1962	1440	5.6	1400	9.4	11	1.2	2.2	7.7	0.36	14
1963	470	3.5	430	7.8	9.4	1.5	0.34	0.71	0.44	14

[a]Values calculated from data supplied by Applied Health Physics Section, ORNL.

[b]Total rare earths less cerium.

Note: Prior to 1949 analysis of water samples was limited to gross beta and gamma determinations.

As activities at ORNL expanded in the 1950's, especially work concerned with chemical extraction of radioisotopes, the quantities of radioactive liquid wastes increased.

From 1946 to 1963 radioactive solids were shipped to ORNL for disposal in "sanitary-landfill" type burial grounds. After 1963 commercial regional burial grounds were established, which have eliminated the further use of ORNL burial grounds for disposal of solid radioactive wastes produced outside Oak Ridge.

Principal Sources

The principal long-lived radionuclides released to the Clinch River from White Oak Creek are ^{144}Ce, ^{137}Cs, ^{60}Co, ^{95}Zr-Ni, ^{106}Ru, ^{90}Sr, and a mixture of other rare earths.[14] No single source of wastes containing these radionuclides exists in White Oak Creek basin. There are several principal and many minor sources within the basin (Fig. 3.6).

Treatment and disposal facilities for liquid wastes include the tank farms, settling basin, and White Oak Lake (all established in 1943), the evaporator (operated from 1949 to 1954), sewage treatment plant (1951), laundry (1955), and the process waste water treatment plant and equalization basin (1958).[15]

[15] F. N. Browder, "Radioactive Waste Management at Oak Ridge National Laboratory," *Industrial Radioactive Waste Disposal, Hearing before the Special Subcommittee on Atomic Energy, Congress of the United States (86th Congress),* Vol. 1, pp. 461–514, U.S. Government Printing Office, Washington, 1959.

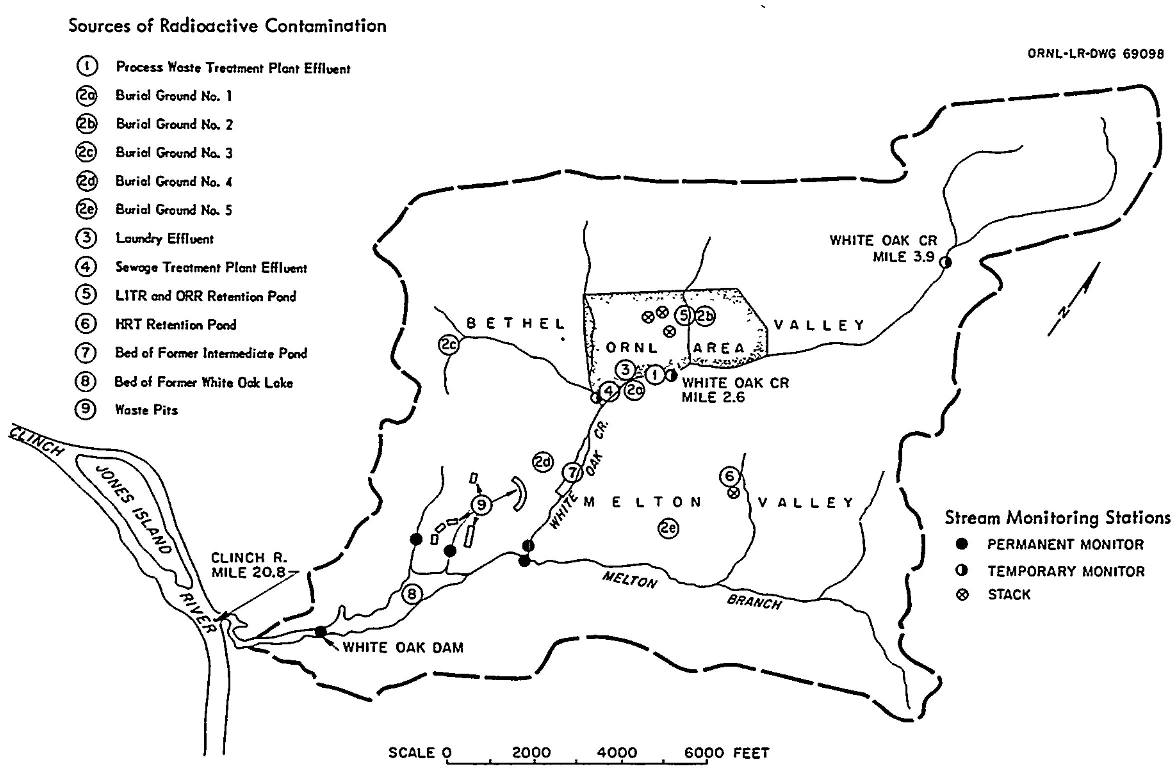

Fig. 3.6. Map of White Oak Creek Basin Showing Sources of Radioactive Contamination and Stream Monitoring Stations.

Only liquids of low radioactive content are released to White Oak Creek from the settling basin, laundry, or sewage treatment plant. Liquid wastes of intermediate activity were held at tank farms or treated in the evaporator until 1951. Since 1951 they have been released to seepage pits and trenches.

Some drainage from pits 2, 3, and 4 formed radioactive seeps along the lower faces of the ridge on which the pits were located.[16] The flow of these seeps drains into White Oak Lake. Radioactivity levels in these surface seeps were extremely low until 1959, when a large volume of highly radioactive liquids was released to the pits.

During the period of the Clinch River Study the principal source of ^{60}Co and ^{106}Ru was seepage from liquid waste pits and trenches (Fig. 3.6).[8,17]

A major source of other radionuclides in the releases at White Oak Dam since 1957 is the effluents from the process waste water treatment plant and from the associated equalization and settling basins.[8] Other sources of radionuclides, especially ^{137}Cs and ^{90}Sr, are those caused by the erosion and leaching of sediments in the former beds of the intermediate pond and White Oak Lake.[16]

Until 1955 White Oak Lake was the final settling basin in a triple-settling process (tanks, settling basin, lake).[15] At one time there was a fourth facility for settling, the intermediate pond (destroyed by flood in 1944).

By 1955 the accumulation of radionuclides in the bottom sediments of White Oak Lake (44 acres) had come into equilibrium with radioactivity in the water.[5] Therefore, since the lake served no useful function in retaining radioactivity, it was drained in October 1955. The lake basin could function, however, as an emergency storage pond in case of an accidental release.

Minor Sources

A large number of sources releasing minor quantities of radionuclides are in White Oak Creek basin. Lomenick[8] has identified at least 20 such sources in the vicinity of the ORNL plant area.

Leaching of radionuclides from solid waste materials in burial grounds by percolating groundwaters is known to occur. However, according to Struxness, no significant quantity of radionuclides has been known to escape from these land fills.[16]

Weapons Test Fallout

Part of the radioactive materials in waters of the Clinch and Tennessee Rivers originated as fallout from weapons testing in the United States and elsewhere. National water-sampling networks of the Geological Survey (tritium fallout) and of the U.S. Public Health Service (^{90}Sr and

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[16]E. G. Struxness, *Detailed Assessment of Solid and Liquid Waste Systems — Hazards Evaluation*, vol. 4, ORNL-CF-60-5-29 (May 31, 1960).

[17]T. F. Lomenick, "Movement of Ruthenium in Bed of White Oak Lake," *Health Phys.* 9, 835–45 (1963).

other radioactivity) have been used to monitor contamination resulting from weapons testing; work by these agencies has shown that fallout in surface waters is appreciable over wide areas of the United States.

In the Clinch River, 16% of the ^{90}Sr was from fallout in the period 1961–62. Measurable quantities of other radionuclides, ^{137}Cs and ^{106}Ru, also originated from fallout.[18]

Other Oak Ridge Facilities

Aside from worldwide fallout, the principal source of fission products in the river waters is from releases through White Oak Dam. Careful monitoring at facilities in Oak Ridge and its vicinity indicates that no significant quantities of radioactive materials have been released into city or plant sanitary sewerage systems.[19]

Summary

Changes in the methods of waste management at ORNL have resulted in the following identifiable changes in the release of radionuclides to the Clinch River (Table 3.3): (1) a decrease accompanying installation of the evaporator in 1949; (2) a high release in 1955 and early 1956 due to the drainage of White Oak Lake; (3) gradual reductions in ^{137}Cs and ^{90}Sr beginning with operation of the process waste water treatment plant in 1957; (4) appreciable releases of ^{106}Ru and ^{60}Co from the seepage pits area beginning in 1959; and (5) a gradual decrease in loads of all radionuclides after 1959 through improvements in the Laboratory's control system.[15]

ROUTINE MONITORING OF THE RIVER FOR RADIOACTIVITY

Programs of monitoring radioactive releases to the environment have existed since the beginning of operations at ORNL. Monitoring of radioactive water and bottom sediments (and also air) has been included in these programs.

Water

Concurrent with the start of operations, monitoring of radioactive waste water began at White Oak Dam. The concentration of radioactive materials in grab samples, collected daily, was determined through gross beta and gamma analysis. The flows over White Oak Dam were computed from water-level records. The daily stream loads of plutonium and other radioactive materials passing over White Oak Dam were reported weekly. Improved radiochemical analysis techniques enabled a change to that of reporting individual radionuclide concentrations in 1949 (Table 3.3).

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[18]M. A. Churchill *et al.*, *Concentrations, Total Stream Loads, and Mass Transport of Radionuclides in the Clinch and Tennessee Rivers, Suppl. No. 1 to Status Report No. 5 on Clinch River Study*, ORNL-3721, Suppl. 1 (August 1965).

[19]Records of USAEC contractors in Oak Ridge and annual health protection review conducted by Oak Ridge Operations, USAEC.

After draining White Oak Lake in October 1955, the flows were estimated for about four years by summing the discharges at streamflow stations on White Oak Creek below ORNL and on Melton Branch and by using an adjustment factor to compensate for the local inflow downstream.[20] Grab sampling at the dam continued during this period.

In 1959 renovation of the gate structure at White Oak Dam to prevent the inflow of backwaters from the Clinch River made possible the reestablishment of a streamflow station. An automatic water sampler, installed the previous year to collect continuous samples, was modified so that sample collection would be in proportion to the flow.

Until 1958 the concentration of radioactive materials in Clinch River waters was computed on the assumption that complete mixing of creek and river waters occurred within a reasonable distance. Monitoring of the radionuclide content of river water began in 1958.

Water-Sampling Stations for Monitoring Radioactive Waters of the Clinch River[a]

Station	CRM	Date of Installation	Frequency of Sampling	Frequency of Analyses
Centers Ferry	4.5	October 1958	Daily	Quarterly
ORGDP water plant	14.4	April 1960	Continuous	Weekly (to March 1963); monthly (thereafter)
Background	33.2	October 1959	Daily	Quarterly
	41.5	January 1962		

[a]W. D. Cottrell, Oak Ridge National Laboratory, personal communication to P. H. Carrigan, Jr., U.S. Geological Survey.

Bottom Sediments

Health physicists at ORNL in surveying the environment had been watchful of the accumulation of radionuclides in bottom sediments in White Oak Creek, especially in those downstream from White Oak Dam. It was noted that radionuclides had become associated with sediments downstream from the dam; radionuclides had become associated also with sediments in the Clinch River, and perhaps in the Tennessee River. Annual surveys, begun in 1951, were made to determine the distribution and levels of radioactivity at the surface of bottom sediments in the rivers.

In surveys of 1951–53 only gamma radiation levels were measured.[21] In subsequent surveys, 1954–64, collection of samples of the upper strata of sediment with a hand dredge was included.

[20]H. H. Abee, *Liquid Waste Monitoring Summary, Techniques and Data, 1948–57,* memorandum report, ORNL, Oct. 22, 1958.

[21]J. M. Garner and O. W. Kochtitzky, "Radioactive Sediments in the Tennessee River System," *J. Sanit. Eng. Div., Am. Soc. Civil Engr.*, SA4, 82, 1051-1 to 1051-20 (August 1956).

Composites of these samples from each observation section were prepared for radiochemical analyses.[22]

Observation sections in the Clinch River extended from the mouth of the river to CRM 27.5 (CRM 21.5, after construction of Melton Hill Dam). In the Tennessee River the most upstream section for the surveys was at TRM 570.8, slightly upstream from the mouth of the Clinch River. The downstream terminus of most surveys (especially since 1957) has been in Guntersville Lake at TRM 354.5. Special surveys in 1952 and 1961 extended to the mouth of the river (Fig. 3.5), to TRM 24.[3,7,8,21–23]

The bottom surveys in 1952 and 1961 were made to gain an overall and comparative picture of the distribution of radioactivity and to determine the downstream limits of contamination.

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[22] W. D. Cottrell, *Radioactivity in Silt of the Clinch and Tennessee Rivers*, ORNL-2847 (Nov. 18, 1959).

[23] R. J. Morton (ed.), *Status Report No. 2 on Clinch River Study, Clinch River Study Steering Committee*, ORNL-3202 (Mar. 30, 1962).

4. Methods Used in the Clinch River Study

INTEGRATED ACTIVITIES AND RESPONSIBILITIES

The major activities of the study included: sampling and analyses of water, of bottom sediments, and fish; hydrologic and hydraulic measurements; systems analysis; and radiation safety analysis. The participation of the various federal and state agencies in these investigational activities is outlined in Table 4.1.

Table 4.1. Summary of Integrated Activities and Responsibilities of Agencies

Activity	Participating Agencies[a]	Agency of Principal Investigators
Water sampling and analysis		TVA, USGS, ORNL
Sampling	ORNL, TVA, USGS, Visking Co.	
Analysis		
Stable chemical	ORNL, TSPCB	
Radiochemical	ORNL, USPHS	
Bottom sediment sampling and analysis		ORNL, USGS, USPHS
Sampling	ORNL, USGS, USPHS	
Analysis		
Dredge samples	ORNL, USPHS	
Core samples	ORNL, USGS	
Biota sampling and analysis		ORNL, USPHS
Sampling	ORNL, USPHS	
Analysis	ORNL, USPHS	
Hydrologic and hydraulic measurements	TVA, USGS	TVA, USGS, ORNL
Tracer tests	ORNL, TVA, USGS	ORNL, USGS
Systems analysis		ORNL, TVA
Mass balance	ORNL, TVA, USGS	
Computer simulation	Harvard University, ORNL	Harvard University
Safety analysis	ORNL, TDPH, TVA, USPHS	ORNL

[a]ORNL: Oak Ridge National Laboratory, TDPH: Tennessee Department of Public Health, TSPCB: Tennessee Stream Pollution Control Board, TVA: Tennessee Valley Authority, USGS: U.S. Geological Survey, USPHS: U.S. Public Health Service.

COOPERATIVE PROGRAMS

1. Operation of a water-sampling network to determine radionuclide transport and water quality in the Clinch and Tennessee Rivers.
2. Sampling of bottom sediments to ascertain the distribution of radionuclides, radiation levels, and physicochemical properties and to inventory their radionuclide content.
3. Determination of radionuclide concentrations in various fish species for use in the evaluation of radiation safety.
4. Observation and measurement of streamflow, velocity, and temperature distributions, cross-sectional profiles, and sediment range surveys.
5. Description of diffusion characteristics of the Clinch River through tracer tests.
6. Determination of the mass balance of radionuclides released to the river basin and computer simulation of radionuclide movement in the Clinch River.
7. Estimation of human exposure to ionizing radiation through consideration of critical radionuclides, principal exposure pathways, and important population groups.

Sustained Programs

Three major programs were sustained throughout the period of the study: sampling and analysis of (1) water, (2) bottom sediments, and (3) fish. The sampling and analytical procedures, data processing methods, and intercomparison of analytical procedures pertinent to these programs are described below.

SAMPLING PROCEDURES

Water

Network. – A network of water-sampling stations was established on White Oak Creek (1 station), the Clinch River (3 stations), and the Tennessee River (3 stations) in November 1960 (see Figs. 4.1 and 4.2). Stations 1 and 4 (Table 4.2) served as background sampling sites, upstream from possible contamination by the releases of radionuclides from White Oak Creek.

Temporary sampling stations on the Clinch River, operated in the summer and fall of 1960, aided in the selection of station location, the frequency and volume of sampling, and the desired analyses for the mass-balance study[1,2] (Table 4.2).

Collection. – At stations 1, 2, and 3, automatic equipment diverted samples from the pump line at predetermined times (Clinch River) or at frequent intervals (White Oak Creek).[2–4] Continuous flows in these lines transported sands easily.[1] Intakes to the lines (and grab-sampling

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[1] R. J. Morton (ed.), *Status Report No. 2 on Clinch River Study, Clinch River Study Steering Committee*, ORNL-3202 (Mar. 30, 1962).

[2] R. J. Morton (ed.), *Status Report No. 1 on Clinch River Study, Clinch River Study Steering Committee*, ORNL-3119 (July 27, 1961).

[3] E. G. Struxness and R. J. Morton, "Radioactive Waste Disposal," *Health Phys. Div. Ann. Progr. Rept. July 31, 1961*, ORNL-3189.

[4] H. H. Abee, personal communication.

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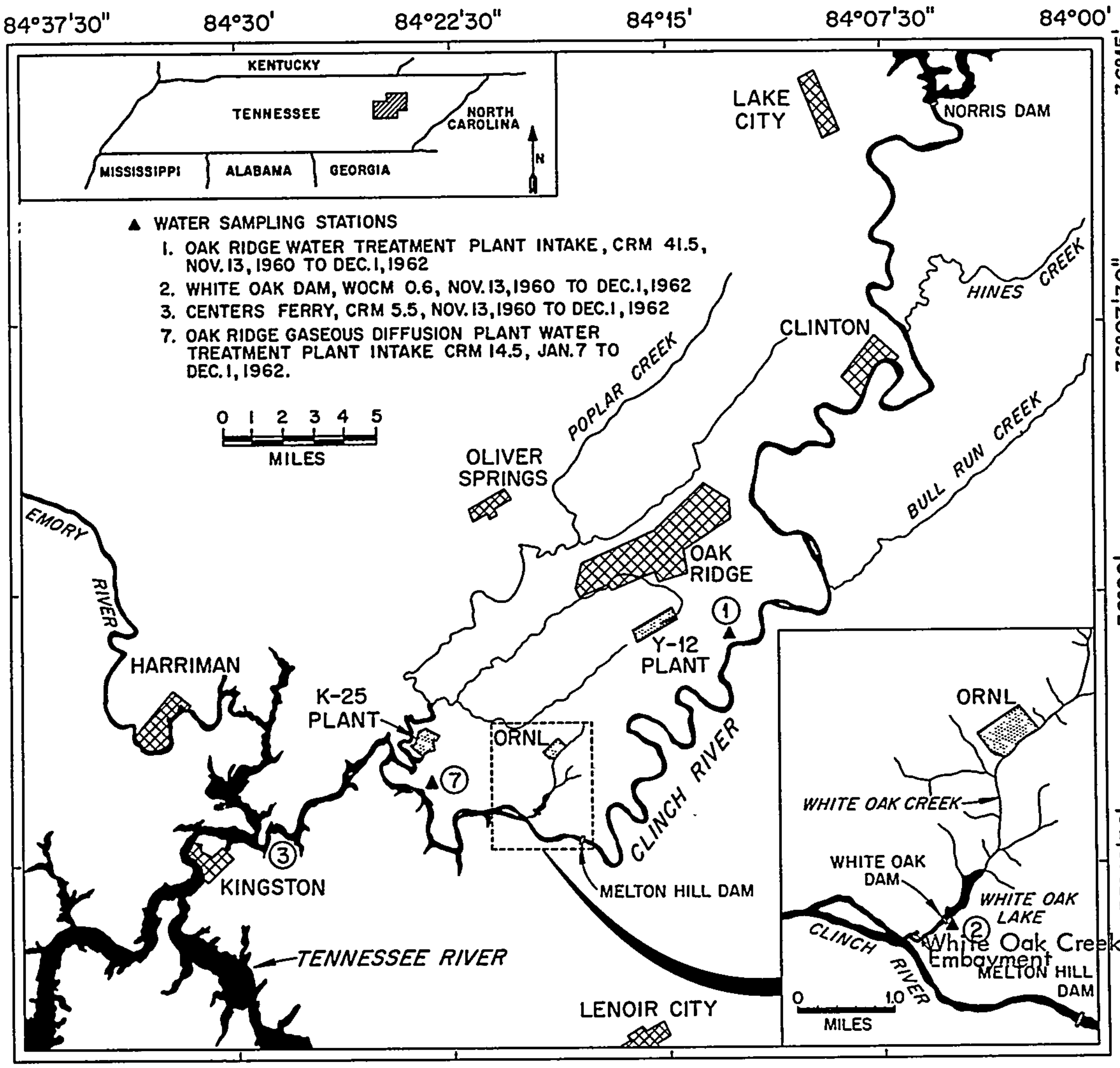

Fig. 4.1. Water-Sampling Stations on White Oak Creek and Clinch River.

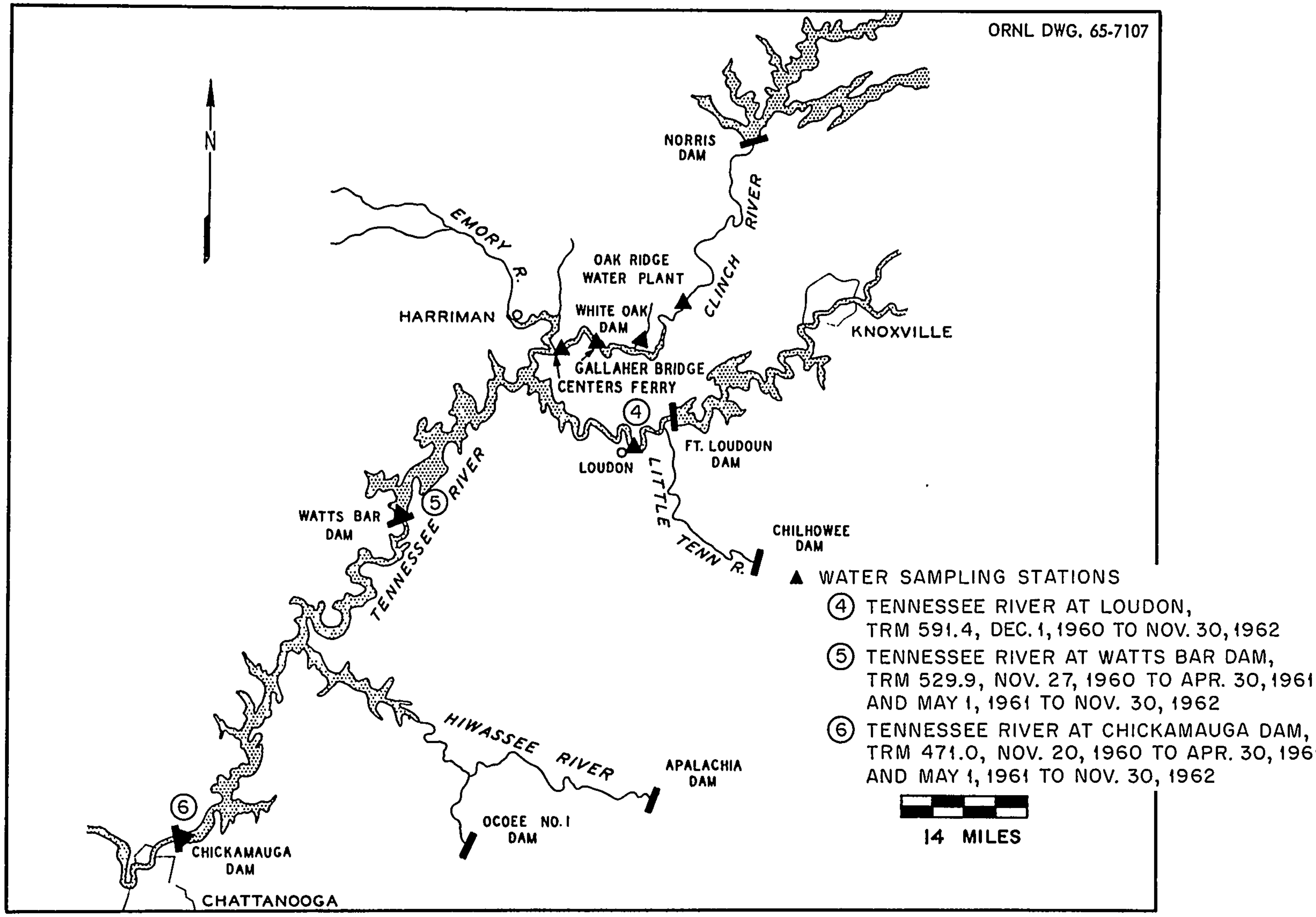

Fig. 4.2. Water-Sampling Stations on Tennessee River.

Table 4.2. Summary of Sampling Procedures for Water-Sampling Network

No.	Station Name	River Mile	Dates of Operation	Type of Sample Collection	Types of Composite Sample: Radiochemical, Week	Radiochemical, Month	Stable Chemical, Week	Stable Chemical, Month	In Proportion to Flow
1	Clinch River at Oak Ridge Water Plant	41.5	Nov. 13, 1960, to Apr. 30, 1961;	Once daily, 2 gal, automatic collection	X		X		X
			May 1, 1961, to Dec. 1, 1962		X			X	X
2	White Oak Creek at White Oak Dam	0.6	Nov. 13, 1960, to Dec. 1, 1962	Continuous, daily automatic collection in proportion to flow	X				X
3	Clinch River above Centers Ferry	5.5	Nov. 13, 1960, to Dec. 1, 1962	Once daily, 2 gal, automatic collection	X		X		X
4	Tennessee River at Loudon	591.4	Dec. 1, 1960, to Nov. 30, 1962	Once daily, 1 gal, grab sample		X		X	
5	Tennessee River at Watts Bar Dam	529.9	Nov. 27, 1960, to Apr. 30, 1961;	Once daily, 1 gal, grab sample	X		X		X
			May 1, 1961, to Dec. 1, 1962		X			X	X
6	Tennessee River at Chickamauga Dam	471.0	Nov. 20, 1960, to Apr. 30, 1961;	Once daily, 1 gal, grab sample	X		X		X
			May 1, 1961, to Dec. 1, 1962		X			X	X
7	Clinch River at ORGDP Water Plant	14.4	Jan. 1960 to Jan. 1962	Twice daily, 1 grab sample	X		X		
			Jan. 7, 1962, to Dec. 1, 1962	Six times daily, 1 liter, automatic collection	X				X

points) were located so that the samples would be representative of the mean concentrations at the sampling sections. At both Watts Bar and Chickamauga Dams a daily grab subsample was collected from the tailrace. The volume of this subsample was proportioned to the volume of river flow which the operator at the dam had been previously instructed to discharge through or over the dam on that day. These daily subsamples were composited at each dam into a weekly sample for analysis.

At station 7, sampling was six times daily to compensate for the effects of severe fluctuations of power releases.

Compositing. – A volume of water proportional to the volume of river flow on the day of sampling was withdrawn from the individual daily samples. Such daily aliquots were then mixed to prepare weekly and monthly composites. The composites ($\sim$8 gal) were split into 1- to 4-liter aliquots, 1-gal aliquots, and 5-gal aliquots for stable- and radiochemical analyses respectively.

Supplemental Sampling. – Grab samples provided water for checks of the tritium content of White Oak Creek, the Clinch River, and other streams in the Oak Ridge area. Analyses of other grab samples from small streams adjacent to White Oak Creek basin and near the Y-12 Plant furnished data to rule out possible contamination from unknown sources of fission products.[5]

USPHS investigators collected water samples quarterly in the Tennessee River basin for their study of the fate of radionuclides discharged to freshwater environments. Reports of their analytical results are in USPHS publications.[6]

The supplemental sampling programs also included analyses in November 1962 and November 1963 for major, minor, and trace-element constituents in alternate weekly composites from station 2. The sampling procedures were those used for the mass-balance study.[7]

Bottom Sediments

Three tools were used for the collection of samples of bottom sediments from the Clinch and Tennessee Rivers: the Phleger-type sampler, the Swedish foil sampler, and Ekman dredges (Figs. 4.3 and 4.4).

Phleger-Type Sampler. – The Phleger-type tool freely falls through the water into the sediment. Drive weights help to obtain full penetration. A plastic liner is in the tool's barrel (inside diameter, $\frac{3}{4}$ in.; length, 14 in.).

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[5]R. J. Morton (ed.), *Status Report No. 5 on Clinch River Study, Clinch River Study Steering Committee,* ORNL-3721 (October 1965).

[6]R. J. Morton (ed.), *Status Report No. 3 on Clinch River Study, Clinch River Study Steering Committee,* ORNL-3370 (Nov. 21, 1962).

[7]R. J. Pickering, "The Chemical Compositions of Clinch River Water and Tennessee River Water and Their Effects on the Fate of Introduced Radioactive Liquid Waste," *U.S. Geological Survey Bulletin* (in preparation).

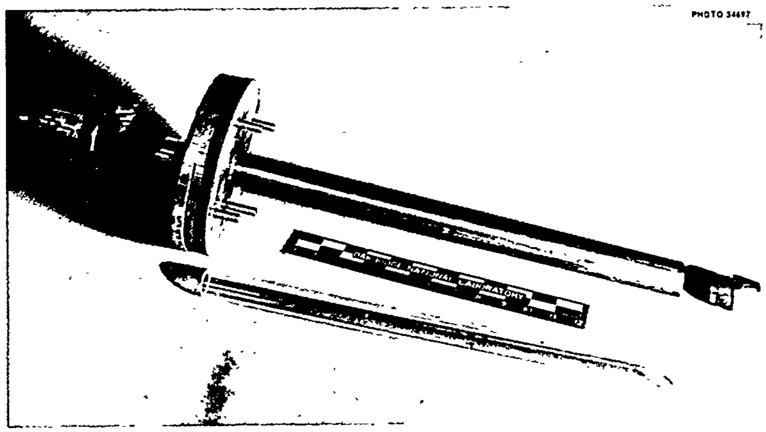

Fig. 4.3. Phleger-Type Bottom Sediment Core Sampler.

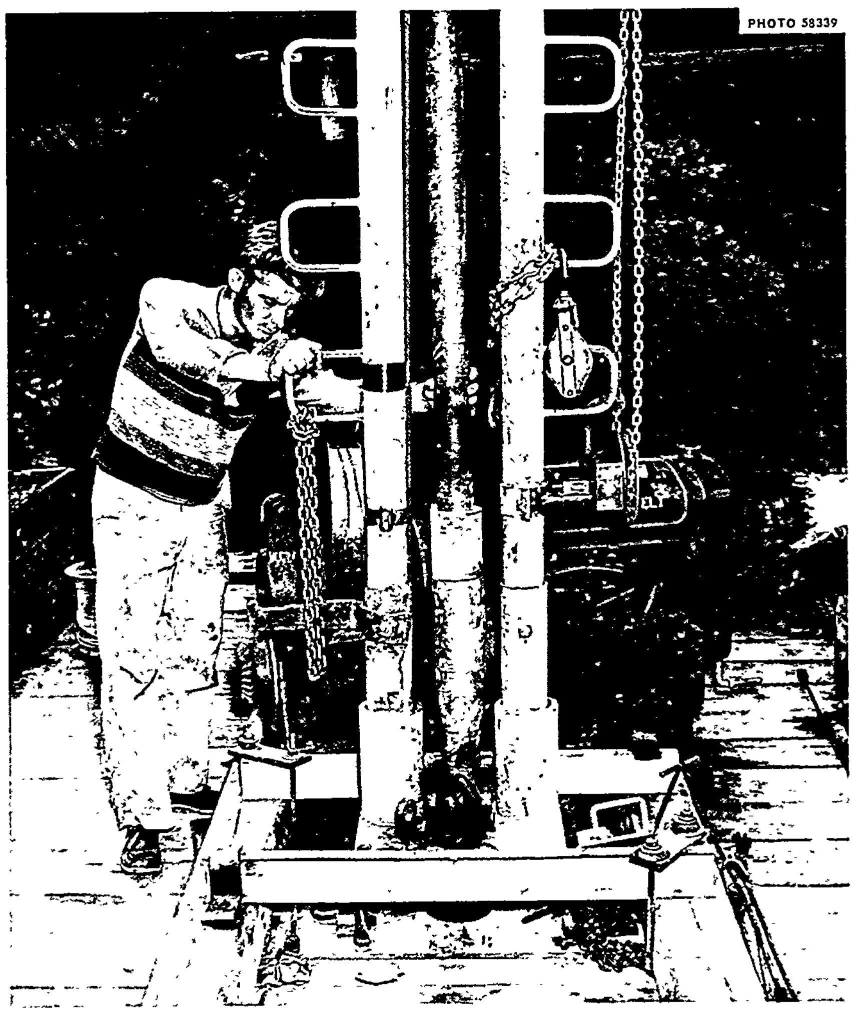

Fig. 4.4. Swedish Foil Sampler in Operation.

This sampler was used in coring programs during the summers of 1960 and 1961. In 1960, sampling was at 19 sections between CRM 1.2 and 22.9 (Fig. 4.5). Coring was attempted at eight to ten equally spaced verticals in the sections. In 1961, coring was at five sections between CRM 4.7 and 19.2 (ten cores per section).

The small diameter of the Phleger-type sampler caused severe compaction of the sample and plugging of the barrel. Consequently, the core lengths were often less than the depth of penetration.[6] The barrel length was also less than the full depth of the sediments at some sections.

Swedish Foil Sampler. – The Swedish foil sampler consists of a variable-length core barrel and sampler head. The barrel is $2\frac{1}{2}$ in. in diameter. Within the sampler head are 16 rolls of thin (0.005-in.) steel foils, $\frac{1}{2}$ in. wide. As the sampler is pushed into the sediment the foils uncoil, forming a casing about the sediment core. The foils act as a liner and eliminate friction between the core barrel and the sediment during driving.[8]

Coring was undertaken with the Swedish foil sampler at fourteen sections of the Clinch River and at two sections each of Emory River and Poplar Creek during the summer of 1962 (Fig. 4.5). Sampling verticals were spaced on the basis of transverse variations in radiation levels at the surface of the sediment, in sectional shape, and in probed depth of sediment.

Ekman Dredge. – Handlines are used to lower dredges with their clamshell jaws open to the surface of the sediment. A light-weight "messenger" drops down the line to trigger jaw closure. The small height of the Ekman dredge (6 in.) permits sampling only of the upper strata of sediment. Dredge samples for desorption studies undertaken at ORNL were collected at the mouth of White Oak Creek (CRM 20.8) and at CRM 15.3. Personnel of the USPHS used dredges in the

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[8]R. J. Pickering, "Use of the Swedish Foil Sampler for Taking Undisturbed Cores of River Bottom Sediment," *Proc. Federal Inter-Agency Sedimentation Conf.*, 1963, *U.S. Dept. Agr. Misc. Publ. 970*, 1965 (in press).

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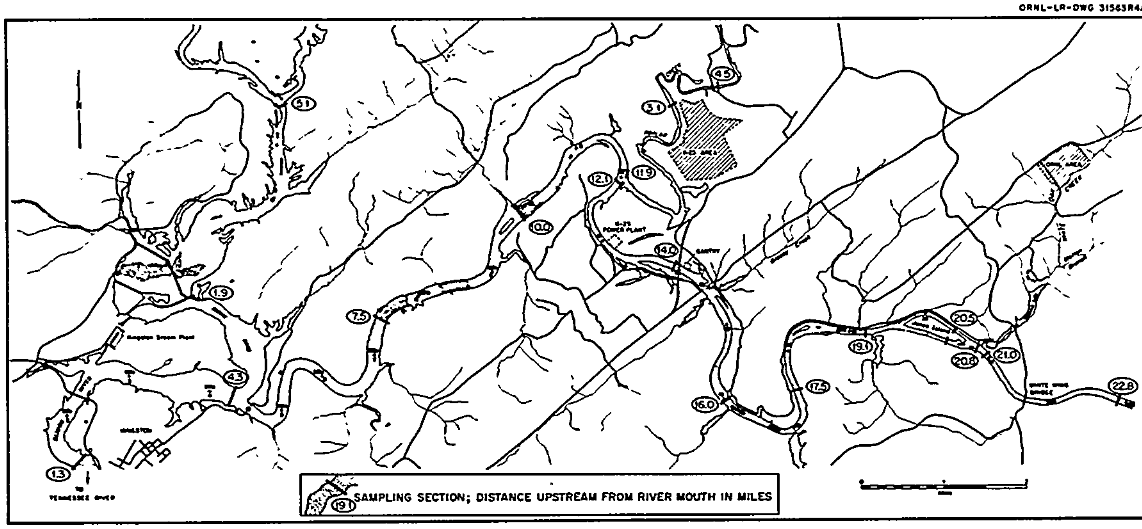

Fig. 4.5. Map of Clinch River Showing Locations of Bottom Sediment Core Sampling Sections.[20]

Clinch River downstream from Norris Dam, in Poplar and White Oak Creeks, and in the Tennessee River from the Clinch River mouth to Chattanooga, Tennessee. This sampling was part of the USPHS environmental program; the analytical results have been reported in USPHS publications.[6]

Fish

Programs of the sampling and analysis included collection of fish for radiation safety evaluation, fish tagging for motility and population studies, and biogeochemical studies.

Radiation Safety Evaluation. – For purposes of the radiation safety evaluation, fish were collected by means of hoop, gill, and trammel nets and by electric shocking. Two series of collections were made, the first in May and June of 1962 and the second in May 1963. Collections were restricted to the Clinch River downstream from the mouth of White Oak Creek. In 1962 the first 40 fish of each of 12 species, both game and commercial species (carp, carpsucker, smallmouth buffalo, golden redhorse), were saved for analysis; the carp and smallmouth buffalo were purchased from commercial fishermen.

Motility and Biogeochemical Studies. – In the tagging operations (July 8 to September 23, 1960, and April 12 to July 7, 1961), fish were caught in hoop nets, identified, measured, weighed, tagged, and released at the site of capture. In 1960 the hoop nets were set from CRM 16.5 to 21.7, while in 1961 the nets were set from CRM 14.0 to 20.8.

White crappies used in the biogeochemical studies were caught in hoop nets set from CRM 10.0 to 10.5. The nets, set each month, remained in place until at least ten fish were caught.

ANALYTICAL PROCEDURES

Water

Radionuclides. – Initially, water samples from the principal network stations were evaporated to dryness for radiochemical analyses. Later, suspended solids larger than approximately 0.7 μ in the 5-gal composites were removed by centrifugation; then the supernatant was concentrated to 3.5 liters by boiling.

Concentrations of ^{137}Cs, ^{60}Co, and ^{106}Ru in the completely evaporated water-sample composite, in the 3.5-liter concentrate, and in the suspended solids were determined by gamma spectrometry.[9] Concentrations of ^{90}Sr were determined by radiochemical separation and beta counting techniques.[10]

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[9]C. R. Porter *et al.*, "Procedure for Determination of Stable Elements and Radionuclides in Environmental Samples," *U.S. Public Health Service, Environmental Health Series, Radiological Health*, January 1965.

[10]P. F. Hallbach (ed.), "Radionuclide Analyses of Environmental Samples," R. A. Taft San. Engr. Center. Tech. Rept. R59-6, U.S. Public Health Serv., Nov. 16, 1959.

Stable Constituents. — Analyses for the major stable-chemical constituents in water samples were performed using Tennessee Stream Pollution Control Board standard procedures.[11] Supplemental water samples were analyzed at ORNL using procedures for radiochemical and stable-chemical analyses described in the ORNL Master Analytical Manual[12] and for minor- and trace-element analyses described in this manual and in reports by Rains *et al.*[13] These samples included those collected at station 2 for stable-chemical determinations, minor- and trace-element determinations at other stations in the network, and radiochemical and stable-chemical analyses for the "index" station (Clinch River at ORGDP water plant intake) prior to its incorporation into the network.

At this latter station, prior to its incorporation in the sampling network, samples were filtered for the removal of sediment particles larger than 0.5 μ, and the filtrate was evaporated to a 25-ml volume before analysis.

Bottom Sediments

USPHS Environmental Program. — The physicochemical properties of bottom-sediment dredge samples obtained by the USPHS were: radionuclide concentrations, particle-size distribution, free iron oxide content, and organic content. Analyses of oven-dried and ash-dry samples included gamma spectrometry,[9] radiochemical separation and beta counting,[10] size analyses by wet sieving and Andersen-pipet methods,[14] organic-content analyses by a potassium dichromate–sulfuric acid digestion technique,[14] and analyses for free iron oxide content.[14]

Desorption. — In a study of the desorption properties of Clinch River sediment, samples (25 g, oven dried) were contacted with 200 ml each of tap water, $NaHSO_3$, $K_2Cr_2O_7$, $CaCl_2$, NaCl, NH_4OH, ethyl alcohol, and acetone. The pH and molarity varied in separate tests with each desorbing solution. Radionuclide concentrations in the dried samples were determined prior to contacting and after 24-hr contact with the desorbing solutions[5] using methods similar to those used in other sorption studies.[15] The radiochemical analyses included gamma spectrometry or radiochemical extraction and beta counting of ^{90}Sr.

Core Analysis. — Cores collected in 1960 were cut into 1-in.-long segments, and the gross gamma radioactivity and wet weight of each segment were determined. Segments from each sampling section were composited, oven dried, and radiochemically analyzed for ^{137}Cs, ^{60}Co, ^{106}Ru, ^{90}Sr, and rare-earth concentrations.[1] Sorptive capacities of the composites were determined using techniques described by Sorathesn *et al.*[15]

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[11] *Water Quality of Tennessee Surface Streams, 1961*, Tennessee Stream Pollution Control Board, Tenn. Dept. Publ. Health, Nashville, Tennessee, July 30, 1962.

[12] H. P. Raaen and A. S. Cline, *Indices, ORNL Master Analytical Manual, 1953–63*, TID-7015 (1964).

[13] T. C. Rains, H. E. Zittel, and M. Ferguson, "Flame Spectrophotometric Determination of Micro Concentrations of Strontium in Calcareous Material," *Anal. Chem.* 34, 778–81 (1962).

[14] M. L. Jackson, *Soil Chemical Analyses — Advanced Course*, College of Agr., Univ. Wisconsin, Madison, 1956.

[15] A. Sorathesn *et al.*, *Mineral and Sediment Affinity for Radionuclides*, ORNL-CF-60-6-93 (1960).

Sectional composites of the 1961 cores were split into halves for particle-size analyses, exchange capacity, and mineral-content analyses. The particle-size analyses were made using wet-sieving and bottom-withdrawal tube methods.[16] Cation and total exchange capacities of the samples were measured by the ammonium chloride techniques.[17] Mineral contents of the sand, silt, and clay fractions of the composites were ascertained with an x-ray diffractometer.

The first step in the processing of 1962 cores was gross gamma scanning. A collimated detector system called a core scanner (Fig. 4.6) was used for this purpose. The scanner automatically counted the gross gamma radioactivity throughout the full length of core in 2-in. increments. In this counting the core remained undisturbed and frozen in its foil and plastic casing. Results of the gross gamma scanning, after digital computer adjustment for imperfect collimation, defined the base of the radioactive zone in the cores and provided criteria for the selection of cores to be used in determining the vertical distribution of gamma-emitting radionuclides.[5]

All cores were cut horizontally at the base of the radioactive zone, and the radioactive portion of the core was cut vertically into quarter cylinders. One of the quarter cylinders was composited, wet and dry weights and volume were measured, and an aliquot of wet composite was set aside for particle-size analysis. The dried composite (100°C) was analyzed for gamma-

[16] *Accuracy of Sediment Size Analyses Made by the Bottom Withdrawal Tube Method,* Report No. 10, Federal Inter-Agency River Basin Comm., St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minn., April 1953.

[17] R. J. Pickering and P. H. Carrigan, Jr., *Radioactivity in Bottom Sediments of Clinch and Tennessee Rivers: Distribution and Inventory in Undistributed Cores from the Clinch River,* ORNL-3721, Suppl. 2B (1967) (in press).

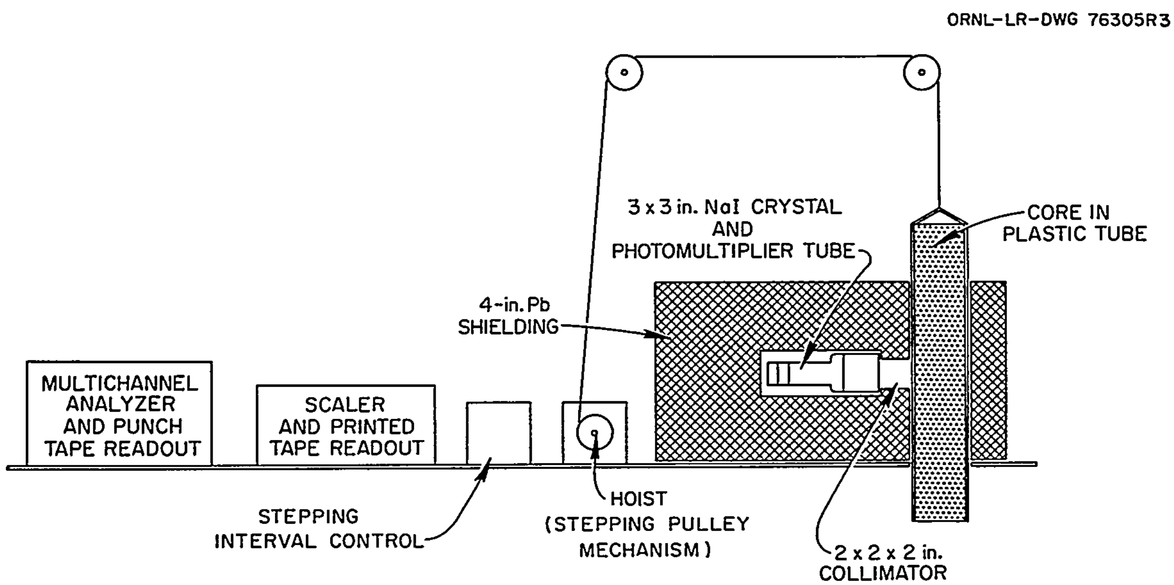

Fig. 4.6. Core Scanner Used for Determinations of Gamma Activity and Gamma Spectra in Sediment Cores. The core was moved past the collimated detector in 2-in. steps.[5]

emitting radionuclides using a pulse-height analyzer and a computer program,[18] and for ^{90}Sr and rare earths by radiochemical separations and beta counting.

The concentration of gamma-emitting radionuclides in 2-in. increments of two selected cores was determined with a pulse-height analyzer. Many physical and chemical analyses were made of these individual 2-in. segments, including carbon mineral, iron oxide, aluminum oxide, minor and trace elements, exchangeable cation contents, particle-size distribution, mineralogy, and exchange capacity.

Fish

Fish for use in the radiation safety analysis were divided randomly for analyses in ORNL and USPHS laboratories. Analyses of the 1962 collection were done according to the flowsheet in Fig. 4.7. Processing of commercial fish (group 1 – carp, smallmouth buffalo, carpsucker, golden redhorse) included bone to approximate commercial preparation methods. The manner of cooking game fish (group 2 – white crappie, bluegill, white bass, largemouth bass, sauger, drum, channel catfish), in preparation for analysis, approximated that normally used by housewives. The 1963 collection of commercial food species was cooked in a pressure cooker at 15 psi for 20 min. All but the flesh and juices were discarded.

White crappie for biogeochemical studies were scaled. A flesh sample was removed without bone contamination, and a bone sample was taken from the vertebral column. After drying, weighing, and ashing and freeing any adhering flesh, all organic matter in the ash was oxidized with HNO_3. The oxidized ash was dissolved in 0.1 N HCl for submission to the analytical laboratory.

Analysis for gamma-emitting radionuclides in the fish was by gamma spectroscopy. Determinations of the ^{90}Sr content of fish were standard wet-chemical procedures and low-background beta counting.

METHODS OF DATA PROCESSING

Water

The weekly loads of radionuclides, both in water and in suspended sediments, were computed for all network stations. The weekly load is the product of the mean weekly concentration and the mean weekly flow of the stream. Two sources of the load in the Clinch River were designated: the background load, measured at CRM 41.5; and the contaminant load, measured at White Oak Dam. Ungaged flows at CRM 5.5 and 14.5 were determined by adjusting for tributary inflows downstream from the streamflow station at CRM 39.0 (Scarboro) or 23.1 (Melton Hill Dam). In the

[18] M. A. Churchill *et al.*, *Concentrations, Total Stream Loads, and Mass Transport of Radionuclides in the Clinch and Tennessee Rivers, Supplement to Status Report No. 5 on Clinch River Study, Clinch River Study Steering Committee*, ORNL-3721, Suppl. 1 (1965).

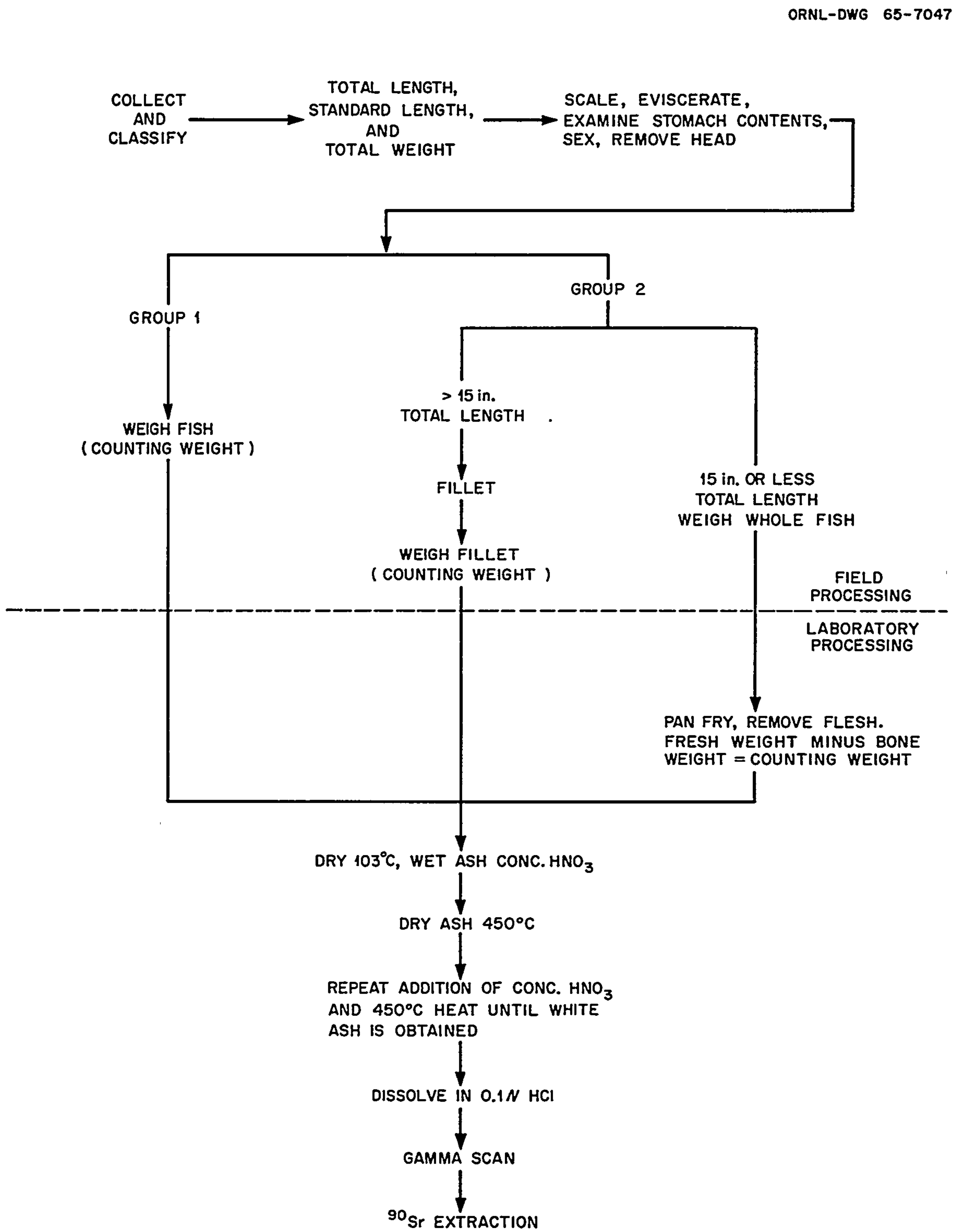

Fig. 4.7. Flowsheet for Preparation of Fish Samples for Radioanalysis.

Tennessee River two sources of the load were designated: the background load, measured at TRM 591.4 (Loudon), and the contaminant load entering from the Clinch River.

The fate of radionuclides was investigated by comparing the input loads to loads transported past the downstream stations using cumulative load curves. The cumulative load curve is a plot of the sum of weekly loads for a specified period vs the duration of the period.

Studies of the stable-chemical characteristics of the Clinch and Tennessee River water were greatly enhanced by statistical treatment of the data. Processing of these data was facilitated through the use of digital computer programs. These programs computed maximum, mean, and minimum concentrations, and the associated standard deviations.

Bottom Sediments

Data on radionuclide content and the physicochemical properties of sediments were statistically analyzed by the USPHS with digital computers. Computer programs were prepared to test the feasibility of replicate sampling and to compute linear regressions of two-variate and multiple-variate systems.[19]

From data of the 1960 coring program, mean gross gamma radioactivity in sampling sections and an inventory of radionuclides in the upper horizon of the bottom sediments were computed, and the vertical distribution of gross gamma radioactivity in individual cores was plotted.[1] The inventory was computed by obtaining the product of the mean concentration of a radionuclide in the sectional composite and the weight of the sediment between sampling sections.[3] Computations required prior determinations of the wet weight of the sediment, its specific gravity, and the widths and depths of subsections of sampled sediments at each section.

From data of the 1962 coring program, vertical distributions of gross gamma radioactivity and of individual radionuclides were determined; mean concentrations of radionuclides, mean depth of the radioactive zone, and volume of radioactive sediment were determined; and an inventory of radionuclides in the study reach was computed. The method of computation was much the same as that used in the 1960 coring program. In the case of the 1962 cores, however, all computations and plots were accomplished with a digital computer program. All computations were based on radionuclide concentration in each core rather than concentration in the sectional composite (as was done in 1960). Extensive measurements of the physical properties of the 1962 cores were made, requiring slightly more computational work than for the 1960 cores.[17]

Similarities in the vertical patterns of gross gamma radioactivity (and of radionuclides) in the 1962 cores and of annual releases through White Oak Dam were quantitatively evaluated by using a digital computer program. Linear regressions statistically compared the radionuclide content of cores to the various physicochemical properties.[17]

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[19]M. Ezekiel and K. A. Fox, *Methods of Correlation and Regression Analysis*, 3rd ed., Wiley, New York, 1965.

Systems Analysis

The Harvard Water Research Group conducted simulation studies of the waste disposal system in the Clinch River to extend the range of data collected in the study. They used a mathematical model developed as a stochastic process to simulate the physical processes and interactions of stream flow, dilution, mixing, nuclear decay, uptake and release from benthal deposits, water withdrawal at use points, and water treatment at downstream use points. Average flows, contaminant inputs, and withdrawals from the Clinch and Tennessee Rivers, based on data developed during the Clinch River Study, were derived for a 200-year period by means of this unique model.

INTERCOMPARISON OF ANALYTICAL PROCEDURES

Water

The water-sampling station at White Oak Dam was operated simultaneously for the Clinch River Study's network and for the routine surveillance program of ORNL's Applied Health Physics Section. Independent radiochemical analyses of the samples from this station by the USPHS and ORNL provided an opportunity for intercomparison of analytical procedures. Intercomparisons of cumulative loads of the important radionuclides were as follows (comparing results from ORNL with those of the USPHS):[18]

Radionuclide	Cumulative Load (curies)		Percent Difference	
	ORNL	PHS	$\frac{\text{ORNL-PHS}}{\text{ORNL}}$	$\frac{\text{PHS-ORNL}}{\text{PHS}}$
^{90}Sr	34.66	39.27	−13.3	+11.7
^{137}Cs	22.17	25.83	−16.5	+14.2
^{60}Co	46.31	51.47	−11.2	+10.0
^{106}Ru	3528	3175	+10.0	−11.1

Sediment

Composites of 11 cores collected in 1962 were selected for intercomparison of analytical procedures. One set of analyses was made by investigators engaged in the study, using a computer program for gamma spectrum analyses;[20] the other was made by the Analytical Chemistry Division in their low-level counting facility. The samples selected were representative of the ranges of radioactivity found in all composites and were from cores collected at verticals well dispersed throughout the study reach. Differences in concentrations of the two important gamma-emitting radionuclides were as follows (comparing results of the investigators with those ob-

[20] E. Schonfeld, A. H. Kibbey, and W. Davis, Jr., *Determinations of Nuclide Concentrations in Solutions Containing Low Levels of Radioactivity by Least-Squares Resolution of the Gamma-Ray Spectra*, ORNL-3744 (January 1965).

tained by the Analytical Chemistry Division at the low-level counting facility):[17] 13.8% for ^{137}Cs and 7.8% for ^{60}Co.

Fish

An intercomparison of analytical determinations of radionuclides in fish was completed in connection with the USPHS-ORNL cooperative fish collection program. Eleven randomly selected samples from ORNL and USPHS were prepared, analyzed, exchanged, and reanalyzed. The intercomparison results are listed in Table 4.3. A delay between collection and the analyses at ORNL accounts for the lack of ^{65}Zn in samples having small quantities of radioactivity. When the means of the concentrations of ^{137}Cs and ^{90}Sr were compared and the equality of the analyses tested statistically, the results from the two laboratories were found to be equal within the 95% confidence level.

Table 4.3. Comparative Radiochemical Analyses of Clinch River Fish[a]

Sample No.	USPHS (picocuries per kg of wet wt)			ORNL (picocuries per kg of wet wt)			
	^{65}Zn	^{137}Cs	^{90}Sr	^{65}Zn	^{106}Ru	^{137}Cs	^{90}Sr
318	*b*	289	2400			319	2191
364	139	366	210			289	223
268	67	653	270			532	314
261	4822	1240	1100	5764		1086	690
332	82	695	800			402	697
277	597	685	1200			509	904
231	10659	1441	1700	8918		563	1527
289	4381	254	220	5100		138	138
303	37	36	140				126
295	2588	135	760	2606		120	541
412	c	*b*	1800			232	1605
109		3492	4900			2875	4851
38		2875	2700			3327	3531
391		1073	680			1180	673
211		472	320			482	616
217		412	120			491	121
221		531	1200			352	1082
414		1948	940			1941	902
157		162	520				686
158		362	370				415
159		720	740			119	783
134		247	100		964	244	198

[a]Aliquots of fish samples were analyzed at ORNL and the USPHS by gamma spectrometry for all isotopes except ^{90}Sr, which was obtained by chemical separation and beta counting.

[b]If blank, none detected or present in amounts too low for accurate interpretation. Other isotopes present in such small quantities included ^{60}Co and ^{95}Zr-^{95}Nb.

[c]Sample lost.

DISPERSION TEST PROCEDURES

Five series of dispersion tests have been conducted in the Clinch River, three of which were carried out as a part of the Clinch River Study. A factor distinguishing one series from another was the tracer used; these tracers were ^{131}I, fluorescein dye, ^{198}Au, potassium chloride–ethyl alcohol solution, and rhodamine-B fluorescent dye. Flows in the Clinch River were steady for the first three tests; flows were variable for the fourth test, conducted in a flume, and for the fifth test, conducted in the Clinch River. The variation in flow simulated the power release patterns to be expected from Melton Hill Lake (Fig. 3.3).

The first two series of dispersion tests, with ^{131}I as the tracer, were conducted July 4–7 and July 9–13, 1957. In each test a large volume of water (several thousand gallons) containing approximately 5 curies of ^{131}I was injected continuously for several hours into White Oak Creek at its mouth. Flows in the creek during these tests were approximately 6.1 cfs; flows in the river were 3000 cfs and 6000 cfs respectively. Observations in the river were made at five cross sections extending from CRM 19.6 to 13.1.

At these sections, radiation levels were observed, and water samples for radiochemical analysis were collected; velocities, temperatures, and water-depth measurements were made at many points in each section. These observations, collections, and measurements were made frequently during the test period. Sufficient data were compiled to describe the distribution of radioactivity, temperature, and velocity in each section.[21]

In the fluorescein-dye test, injections were made on several days. Each day several gallons of dye solution were injected for a period of several minutes (up to 30 min) into White Oak Creek at its mouth. Investigators mapped the spread of the dye front in the Clinch River at 5- to 10-min intervals. At the same time, flows and temperatures in the creek and the river were measured.[22] The study reach was restricted to the vicinity of the mouth of the creek and of Jones Island (Fig. 4.5).

Gold-198 was used as a tracer in two tests, August 1961 and February 1962. Gold solutions containing 7.5 and 9.7 curies, respectively, were injected at the mouth of White Oak Creek in about 1 min. Flows in the Clinch River were steady, at 7990 and 20,200 cfs respectively; flows in the creek were also steady, being 6.7 and 17 cfs respectively. Observations of the passage of the radioactive cloud (concentration-time curve) were made using battery-operated, portable scintillation crystal detectors and scalers. Observation sections in the Clinch River extended from CRM 20.8 down to CRM 4.4. In both tests, observations at some verticals were made at selected depths below the water surface.[6,23]

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[21]E. G. Struxness, "Radioactive Waste Disposal Research and Engineering," *Health Phys. Div. Ann. Progr. Rept. July 31, 1958*, ORNL-2590 (1958).

[22]F. L. Parker, unpublished data.

[23]R. J. Morton (ed.), *Status Report No. 4 on Clinch River Study, Clinch River Study Steering Committee*, ORNL-3409 (Sept. 11, 1963).

In the fall of 1962 a series of flume tests, using an aqueous solution of potassium chloride–ethyl alcohol as a tracer, were made in a $3\frac{1}{2}$- by 150-ft tilting flume. A number of conductivity probes connected to a recording conductivity bridge were positioned in the flume to record concentration-time curves of the passage of the tracer. The width, slope, and roughness of the test channel in the flume were adjusted to simulate a variety of power-release-flow regime conditions of the Clinch River on a distorted scale. The desired model discharge was established in a bypass channel in the flume, then suddenly diverted into the test channel, simulating startup of power releases from Melton Hill. Time of travel of the tracer, time of travel of the discharge wave, water-surface profile for steady flow, and discharge were observed in these tests. The length of the test channel was equivalent to the reach extending from CRM 15.9 to 20.8.

In the summer of 1963 and the spring of 1964, rhodamine-B dye was used as a tracer. Two major tests in this series were made, one in late August 1963, and the other in early April 1964. Dye was injected for a period of seven days in the first test and five days in the second test. The injections were made into water flowing over White Oak Dam. Determinations of the concentration of dye in waters of the Clinch River were made, principally at CRM 5.5 and 14.4, using continuous-flow, recording fluorometers. During these tests, power releases were simulated by releasing waters from Melton Hill through the spillway gates of the dam in patterns similar to those shown in Fig. 3.3. In addition to measurement of dye concentrations, water levels were recorded in the creek and in the river, temperatures were observed continuously at the fluorometer stations, making it possible to obtain longitudinal and vertical temperature profiles, and flows were measured. Supplement water samples were collected at critical times during the passage of dye clouds and at bihourly intervals at White Oak Dam for radiochemical analyses.[5,24]

METHOD OF RADIATION SAFETY ANALYSIS

The most important radionuclides released to the Clinch River are ^{90}Sr, ^{137}Cs, ^{106}Ru, and ^{60}Co. Critical avenues of exposure might include: (1) consumption of contaminated water and fish, (2) exposure to contaminated water and bottom sediments during recreational and industrial use of the water, (3) exposure to radionuclides in sludge and deposits in water systems utilizing river water, and (4) consumption of agricultural produce that may be irrigated with river water.

An important objective of the radiation safety study was to establish the critical nuclides and identify the critical exposure pathways so that an estimate could be made of radiation doses to various population groups.

Organs selected for the analyses included bone, gastrointestinal tract, thyroid, and total body. Insight concerning the potentially critical organs was gained by considering the important radionuclides, the potentially critical avenues of exposure, and the type of individual or population group under consideration.

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[24] R. J. Morton (ed.), *Status Report No. 6 on Clinch River Study, Clinch River Study Steering Committee*, ORNL-3941 (November 1966).

On these bases, estimates of human exposure resulting from contamination in the Clinch and Tennessee Rivers were made. Exposures were calculated from measurements of concentrations of radioactive materials in the various environmental media and assumptions as to the fraction of this material that might be taken in by the exposed population groups. Correction factors were applied to all internal-dose calculations, taking into account differences in the rate of fluid intake and in the mass of critical organs as a function of age.

5. Radionuclide Transport and Accumulation in Clinch-Tennessee Rivers

PHYSICOCHEMICAL ASPECTS

The rate and extent of radionuclide transport and accumulation in the Clinch and Tennessee Rivers are influenced by certain physicochemical aspects of the river-reservoir system. Some of the pertinent variables are rate of water discharge, water velocity, velocity distribution in the cross section, and the physical and mineral qualities of the flowing waters. These factors control or influence the rate and/or extent of dispersion, sedimentation, sorption, precipitation, oxidation, and reduction of the radioactive materials discharged into the Clinch-Tennessee system from White Oak Creek.

Water Velocities and Temperatures in Clinch River Arm of Watts Bar Reservoir

The cross-sectional velocity and temperature distributions at CRM 19.1 for winter conditions are shown in Fig. 5.1 (ref. 1). Similar information at CRM 19.6 for summer conditions is shown in Fig. 5.2 (ref. 2). The average velocities in the river for winter conditions, Watts Bar elevation 735, and summer conditions, Watts Bar elevation 741, are shown in Table 5.1.

Density underflows exist in the lower end of the Clinch River arm of Watts Bar Reservoir during all periods in the summer months when cool inflows are in excess of perhaps 1,000 cfs but do not exceed 7,000 to 12,000 cfs. When cool inflows exceed 7,000 to 12,000 cfs (the value depending on the difference in density of the inflowing and pooled waters), the inflowing cool water occupies essentially the entire cross section of the reservoir, even near the mouth of the river, and thus no "underflow" can develop in the Clinch River arm of Watts Bar Reservoir. These underflows are produced by the difference in density between the cool waters released upstream at Norris Dam during the summer months and warmer inflows from local unregulated streams. The radioactive wastes discharged from White Oak Creek are mixed into the cool water upstream from the point in the lower end of the Clinch embayment at which the cool waters sink beneath the surface of the embayment and form a density underflow. The underflows of cool

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[1]R. J. Morton (ed.) *et al.*, *Status Report No. 2 on Clinch River Study*, Clinch River Study Steering Committee, ORNL-3202 (Mar. 30, 1962).

[2]K. Z. Morgan *et al.*, *Health Phys. Div. Ann. Progr. Rept. July 31, 1958*, ORNL-2590, p. 20.

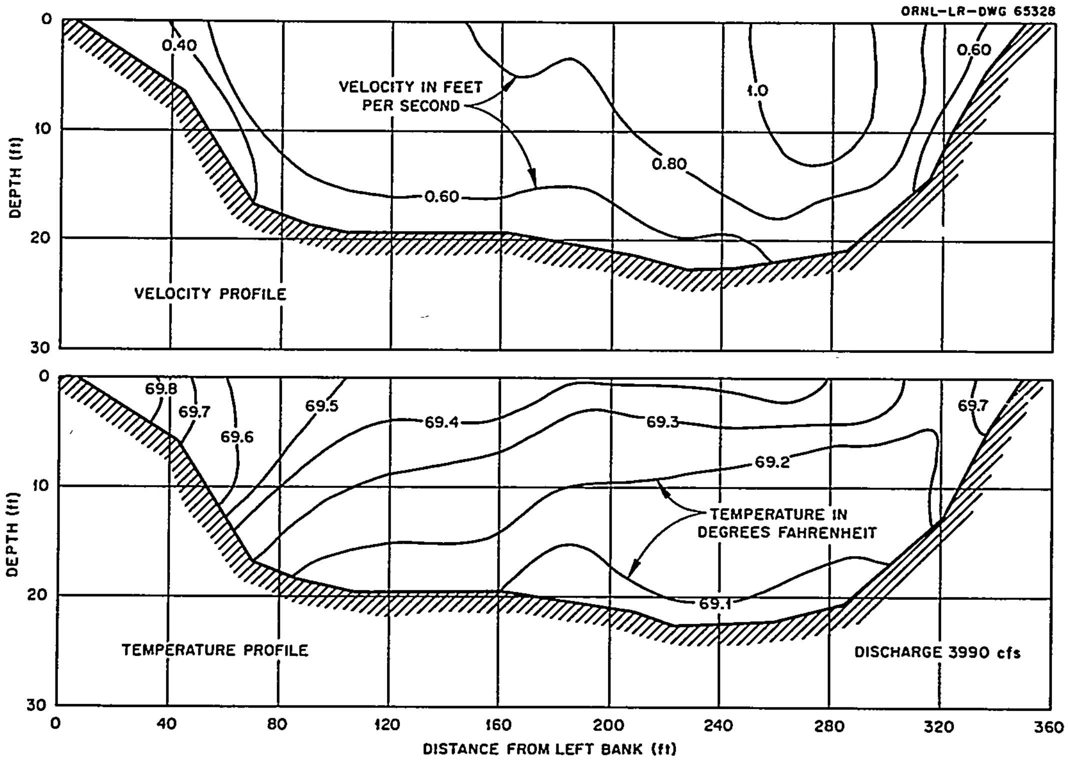

Fig. 5.1. Temperature and Velocity Profiles at Clinch River Mile 19.1, October 12, 1960.

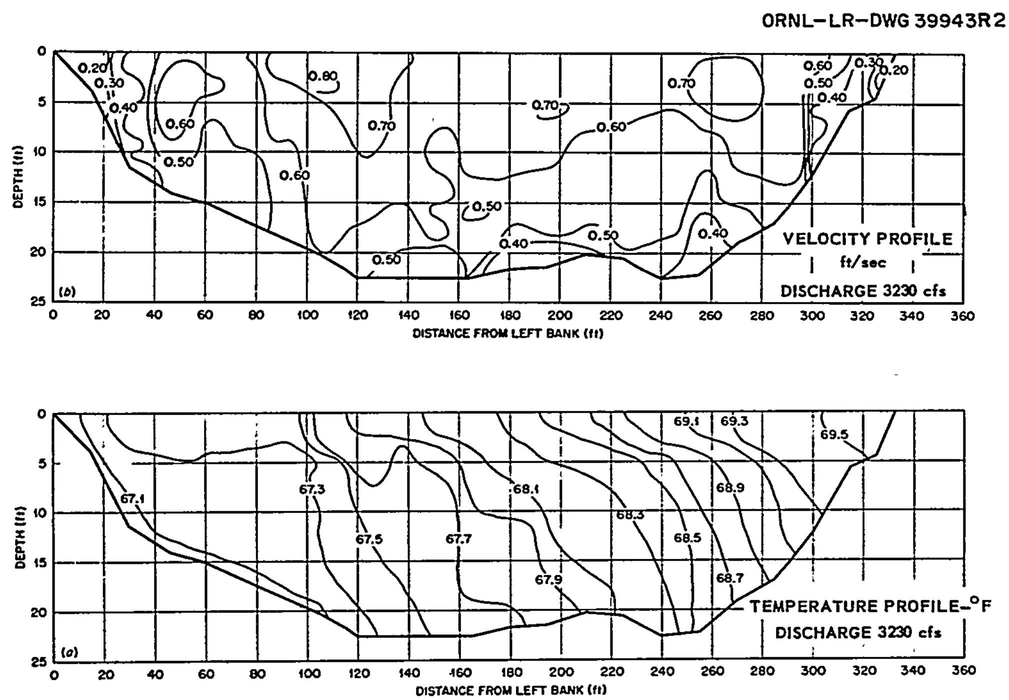

Fig. 5.2. Temperature and Velocity Profiles at Clinch River Mile 19.6, July 3, 1957.

Table 5.1. Average Velocities of the Flowing Water in Clinch River Arm of Watts Bar Reservoir (fps)

Discharge (cfs)	Winter (Watts Bar Elev. 735)		Summer (Watts Bar Elev. 741)	
	Calculated	Observed	Calculated	Observed
1,000	0.09		0.13	
5,000	0.45		0.45	
8,000	0.7		0.61	0.8
10,000	0.9		0.67	
15,000	1.4		0.98	
20,000	1.7	1.7	1.3	

Clinch River waters continue throughout the downstream main-river segment of Watts Bar Reservoir.[3] At Watts Bar Dam water in these underflows is mixed with water flowing down the Tennessee River from above Kingston as both Clinch and Tennessee waters pass through the turbines into the tailrace.

The presence of these underflows in the Clinch River during the summer months accounts for the higher average velocities at low flows during the summer months shown in Table 5.1, even though the pool level is higher (and thus the total cross-sectional area is greater) during the summer than during the winter.

Water Quality

The mineral qualities of water in the Clinch and Tennessee Rivers and in White Oak Creek (Table 5.2) reflect the geology of the areas through which they flow. Consequently, in the Clinch River, which drains a limestone region, one would expect to find, and indeed does find, relatively high concentrations of $Ca(HCO_3)_2$ in the water.[4] Concentrations of magnesium from dolomites are also relatively higher in the Clinch waters than in the waters of the Tennessee. Since both calcium and magnesium are the principal minerals causing water to be hard, waters of the Clinch are significantly harder than in the Tennessee. Some of the principal tributaries of the Tennessee River above the mouth of the Clinch drain mountainous areas of eastern Tennessee and western North Carolina, and since these areas are underlain predominantly by less soluble siliceous rock formations, the water draining from these areas is much lower in calcium and magnesium, and thus is much softer.[4]

The higher chloride content of the Tennessee River is due primarily to industrial operations on the North Fork Holston River and to the higher sodium chloride content of groundwater draining

[3] A. S. Fry, M. A. Churchill, and R. A. Elder, "Significant Effects of Density Currents in TVA's Integrated Reservoir System," *Proc. Minn. Intern. Hydraulics Conv.*, September 1953.

[4] R. J. Morton (ed.) *et al.*, *Status Report No. 5 on Clinch River Study*, Clinch River Study Steering Committee, ORNL-3721, pp. 19–20 (October 1965).

Table 5.2. Summary of Discharge-Weighted Mean Values[a] of Stable Chemical Analyses[b] of Clinch and Tennessee River Water[c]

	CRM[d] 41.5	WOD[e]	CRM[f] 14.4	CRM[d] 5.5	TRM[g] 591.4	TRM[d] 529.9	TRM[d] 471.0
Turbidity	28			17	14	6	7
Apparent color	197			114	88	53	59
Centrifuged color	20			20	23	24	31
pH	7.8		7.7	7.7	7.8	7.6	7.7
Bicarbonate	117	125	119	112	66	70	63
Acidity, as $CaCO_3$	3			4	3	3	3
Hardness, as $CaCO_3$	107			106	75	75	70
Calcium	27	32	21	27	21	20	19
Magnesium	9.4	6.0	7.7	9.4	5.5	5.8	5.5
Chloride	5	5.1	1.6	3	20	15	13
Sulfate	12	23	10	12	11	12	12
Nitrate	1.0	8.2	2.7	1.5	1.8	1.6	1.5
Iron	3.4	0.08	0.06	1.7	1.0	0.5	0.6
Phosphate	0.2	0.60	0.22	0.1	0.2	0.2	0.1
Potassium	1.7	1.6	1.3	1.6	1.3	1.8	1.3
Sodium	2.3	1.4	2.4	2.4	9.5	6.8	5.8
Silicon	2.9	1.7	1.5	2.7	3.5	3.1	3.4
Specific conductance	195	283	216	196	170	177	162
Suspended solid	185		25.3	55	22	15	9
Dissolved solid	125		129	133	121	112	101
Total solids	310		154	188	142	126	111
Organic nitrogen	0.7			0.5		0.5	0.4
Manganese	0.4			0.1	0.1	~0.0	~0.0
Chromium	0.02[h]						
Strontium	0.073[i]	0.065	0.070	0.069	0.063		
Discharge[j]	5088	14	4620	5585	21,419	31,340	38,876

[a]Concentrations in mg/liter, except pH in pH units, specific conductance in micromhos/cm, and discharge in cfs.

[b]Chemical analyses performed on filtered samples from CRM 14.1, White Oak Creek Dam. For other stations, chemical analyses performed on unfiltered (raw) samples.

[c]Values for TRM 591.4 are arithmetic averages of monthly samples which were not discharge-weighted when composited, as were samples for other stations.

[d]Sample period, Nov. 27, 1960–Dec. 1, 1962.

[e]Sample period, Nov. 18, 1961–Nov. 30, 1963, at White Oak Dam.

[f]Sample period, Nov. 28, 1960–Jan. 8, 1962.

[g]Sample period, Aug. 1960–Nov. 1962.

[h]Sample period, May 1961–Nov. 1962 only.

[i]Sample period, Mar. 19, 1961–Jan. 6, 1962 only.

[j]Time-weighted mean for the total sampling period.

into the upper reaches of the North Fork Holston River. Although nitrate and sulfate concentrations were high in White Oak Creek water, 8.2 and 23 mg/liter, respectively, for the period November 1962 to November 1963, the dilution provided by the Clinch River is so great that concentrations of nitrates and sulfates in the Clinch downstream from White Oak Creek are not markedly affected. The concentrations of iron shown reflect primarily the oxidized iron present in suspended sediment particles. Since the waters of both the Clinch and Tennessee Rivers are well supplied with dissolved oxygen, there could be no unoxidized (soluble) iron present in these waters.[5] Except for the radioactive contents, the mineral quality of water in the Clinch downstream from Oak Ridge is essentially the same as that upstream (Table 5.2).

In general, concentrations of suspended sediments in the Clinch River are quite low, due to sedimentation in Norris Reservoir. During high rainfall and runoff, however, concentrations increase somewhat. The average concentration of suspended sediment, based on monthly sampling at Clinch River mile 41.5, was 185 mg/liter, with a maximum of 557 mg/liter and a minimum of 18 mg/liter. Farther downstream at Clinch River mile 5.5 in the Clinch River embayment of Watts Bar Reservoir, in which embayment some sedimentation occurs, the mean concentration of suspended sediment based on weekly sampling was 55 mg/liter. Actual measurements by TVA of bottom sediments in the river between miles 22.8 and 1.3 during the period June 1961 to June 1962 showed an average deposition of 2.1 ft.[6]

In summary, water in both the Clinch and Tennessee Rivers is slightly basic, is moderately hard, and normally has a relatively low concentration of suspended solids.

DOWNSTREAM TRANSPORT OF RADIONUCLIDES

The cumulative curves for the mass-balance analysis of the downstream transport of the major radionuclides, ^{90}Sr, ^{106}Ru, ^{60}Co and ^{137}Cs, entering into the Clinch River at Oak Ridge are shown in Figs. 5.3–5.6.[7] As explained in detail in Chap. 4, the cumulative load for each radionuclide at each sampling station is the cumulative sum of the weekly loads passing that station. The total loads passing the downstream stations can easily be compared with loads passing the upstream stations to determine whether any significant loss occurred between stations as, for example, by sorption by suspended sediment for later deposition, or by sorption by the biota and/or bottom muds. Obviously any significant gains in load between stations can also be detected quite readily.

To permit comparison of the total cumulative loads at successive stations, an estimate of the "normal" time of water travel from station to station was made, and lagged time scales were used for plotting the loads accordingly. For example, water flowing out of the mouth of White Oak

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[5] R. J. Pickering, "Stable Chemical Analysis of Clinch and Tennessee River Water," presented at Clinch River Study Steering Committee meeting, December 1963, p. 3.

[6] Calculated from Tennessee Valley Authority sediment range data.

[7] M. A. Churchill *et al.*, *Concentrations, Total Stream Loads, and Mass Transport of Radionuclides in the Clinch and Tennessee Rivers*, ORNL-3721, Suppl. 1 (August 1965).

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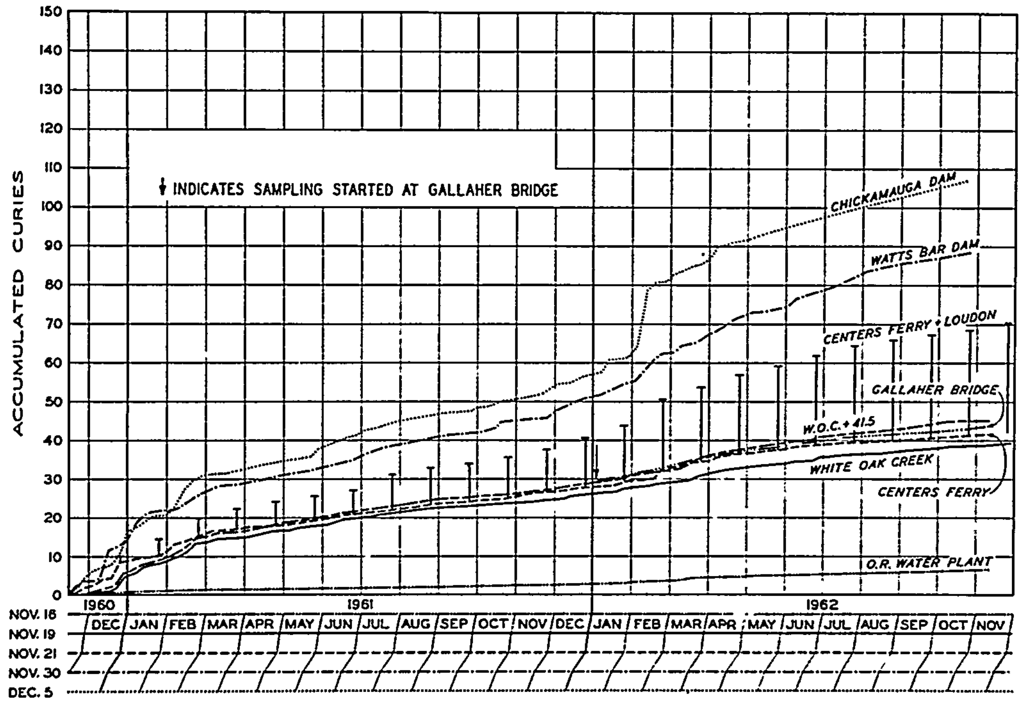

Fig. 5.3. Mass Diagram ^{90}Sr.

ORNL-DWG 65-3194R

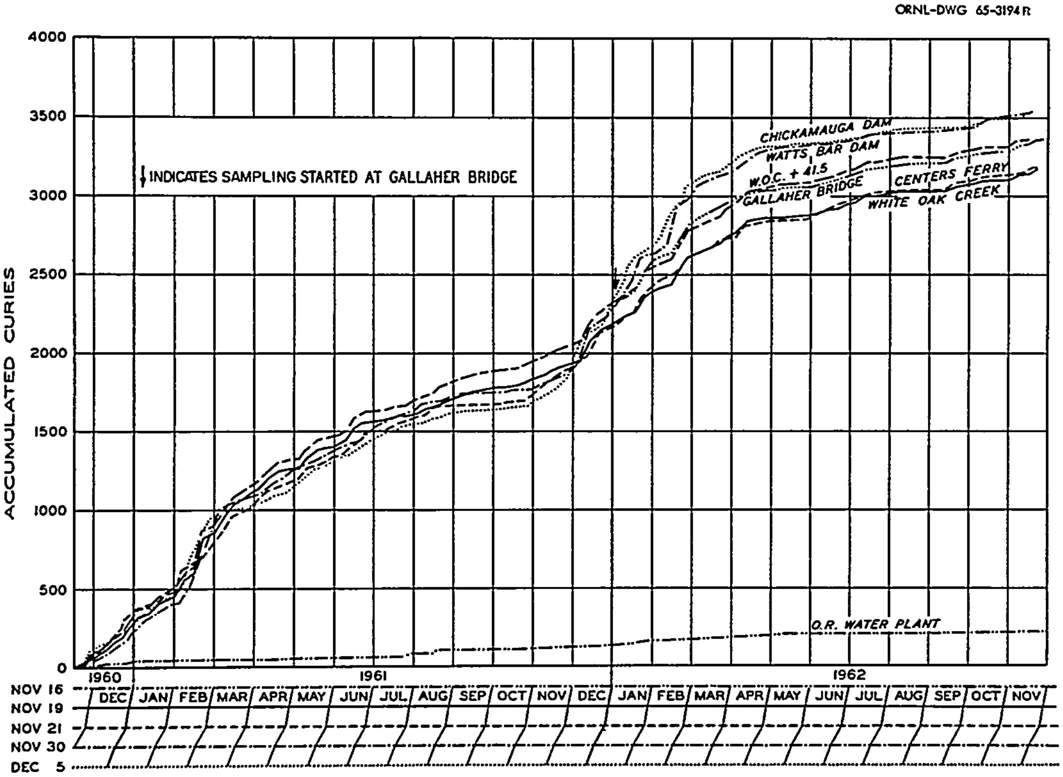

Fig. 5.4. Mass Diagram ^{106}Ru.

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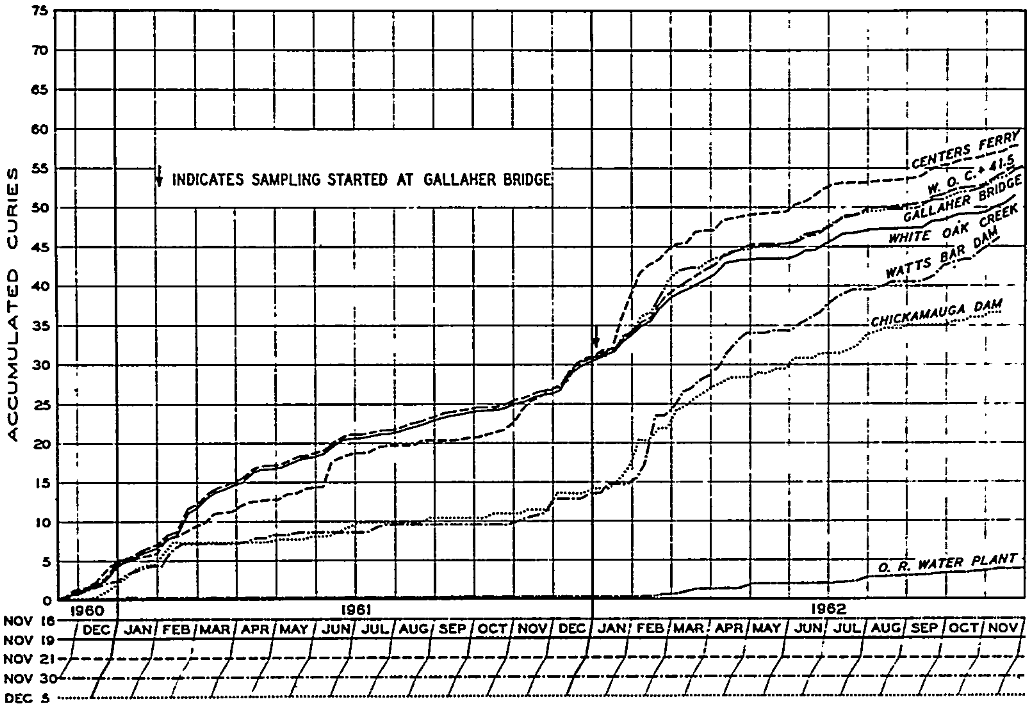

Fig. 5.5. Mass Diagram ^{60}Co.

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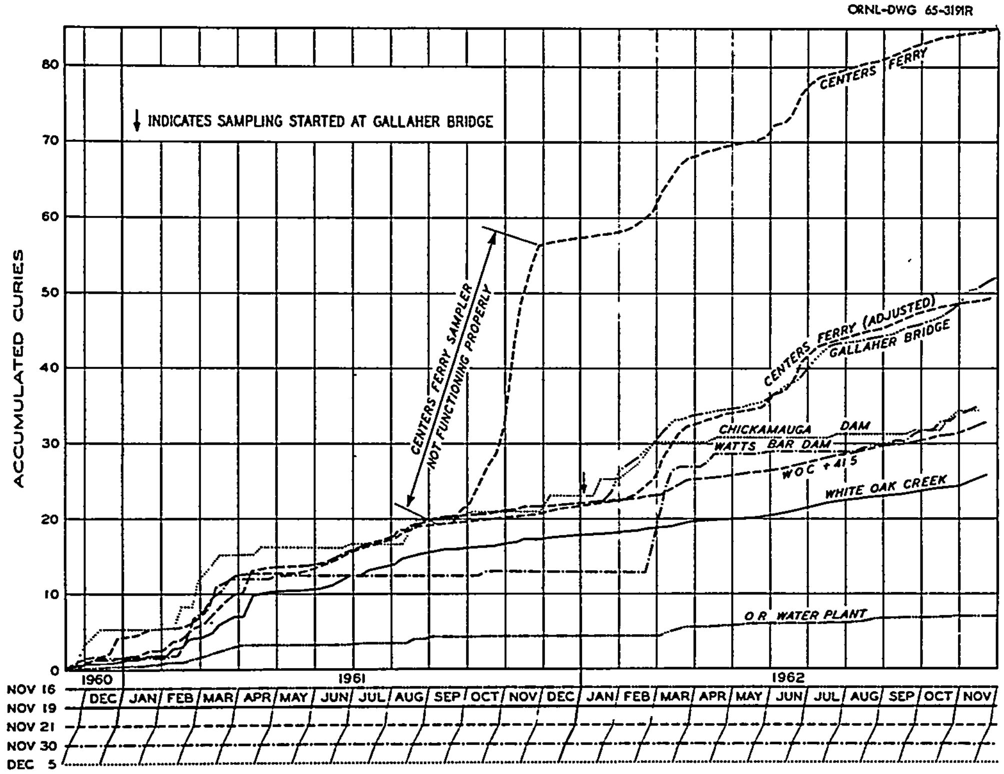

Fig. 5.6. Mass Diagram ^{137}Cs.

Creek would be expected to arrive at the Centers Ferry station (Clinch River mile 5.5) two days later, at Watts Bar Dam nine days later, and at Chickamauga Dam after five more days. Naturally these times are not constant but vary with streamflows, with pool levels, and to some extent with the season of the year. A constant time of travel has been assumed, however, as detailed above, and the plotted data seem to support, over all, the estimated times reasonably well.

Pertinent to the accuracy and dependability of the mass-balance analysis shown below are values of the lower limits of detection for the individual radionuclides.[7] The great dilution provided by the high flows in the Tennessee River results in a lower level of accuracy for the mass curves computed for the stations on the Tennessee River.

Lower Limits of Detection for Individual Radionuclides
(curies/liter)

	^{90}Sr	^{106}Ru	^{60}Co	^{137}Cs
	$\times 10^{-12}$	$\times 10^{-12}$	$\times 10^{-12}$	$\times 10^{-12}$
White Oak Creek	1	45	9	11
White Oak Creek (D S[a] only)	1	190	44	67
Other stations	0.03	2	1	1
Other stations (D S only)	0.03		2	4

[a]D S = dissolved solids.

Strontium-90[7]

The mass diagram for ^{90}Sr, Fig. 5.3, indicates essentially no loss or gain in total cumulative load between the dam on White Oak Creek and the station at Centers Ferry near the mouth of the Clinch River. Although the samples at Loudoun were not flow proportioned, if it is assumed that they were, the cumulative loads here would be those indicated in Fig. 5.3 by the length of the vertical bars extending upward from the Centers Ferry load curve. This load was presumably derived from fallout on the 12,220 square miles of drainage area above this station. Additional significant gains in total accumulated loads are indicated to have occurred between Centers Ferry plus Loudon and Watts Bar Dam, and between Watts Bar and Chickamauga Dams. This fallout could have been derived from the numerous weapons tests (Russian and American) during the months of September, October, and November 1961. From these curves and other supporting data it can be concluded that a very high percentage of the ^{90}Sr released to the river at Oak Ridge arrives at Chattanooga, some 120 river miles downstream.

Ruthenium-106[7]

Throughout the two-year period of sampling, the mass diagram for ^{106}Ru, Fig. 5.4, for Centers Ferry is practically identical to the one for White Oak Creek. Likewise, during the last 11 months of record the curve for White Oak Creek plus the Oak Ridge water plant is nearly identical to that for Gallaher Bridge. Throughout the entire period of record, the curves for Watts Bar Dam and Chickamauga Dam are essentially the same.

Based on the rather amazing agreement between the cumulative loads measured at all stations below White Oak Dam with the load measured at White Oak Dam, it can be definitely concluded that during the two-year sampling period essentially all the ^{106}Ru discharged from Oak Ridge passed through the river system to Chattanooga in the water phase. The ^{106}Ru that is found in bottom sediments between Oak Ridge and Chattanooga must represent the continued accumulation over the years of a very small percentage of the load discharged at Oak Ridge.

The amazing agreement between the ^{106}Ru curves at the downstream stations is an indication that, with high enough radionuclide concentrations to permit statistically satisfactory counting, good mass-balance results can be obtained even though the flow volumes by which the concentrations are multiplied are large.

Cobalt-60[7]

Figure 5.5 shows mass-balance curves of ^{60}Co. The curves for White Oak Dam, Gallaher Bridge, and Centers Ferry plot reasonably close together throughout the period of record. Thus, there seems to have been no significant loss of this radionuclide in the Clinch River. Actually there was an apparent gain in load at Centers Ferry during January and February 1962. However, because of malfunctioning of the sampling equipment at the Centers Ferry station, the reported load at this station might be incorrect. If the curve value for December 1, 1961, is adjusted to about 22 curies (the value obtained by extending the curve established prior to about October 1), and if the load thereafter is accumulated from this value, the mass curve for this station would fall slightly below the curve for Gallaher Bridge. The total load for the two-year sampling period would be about 53 curies. The curves could then be interpreted as showing a very slight loss of ^{60}Co in the Clinch River.

Curves for both Watts Bar and Chickamauga Dams indicate a cumulative loss from the load measured at both White Oak Dam and Centers Ferry. However, most of this loss is indicated to have occurred during the spring and summer of 1961. From November 1961 through November 1962, the curves for White Oak Creek and Chickamauga Dam are surprisingly parallel. Thus, during this period, the only effect discernible in the river system was dilution, since the load going in at White Oak Dam arrived later, undiminished, at Chattanooga.

Cesium-137[7]

Mass diagrams for ^{137}Cs are shown in Fig. 5.6. The accuracy of these curves is subject to question since in sample analysis the ^{137}Cs spectrum was masked by the peaks due to the high concentrations of ^{106}Ru in the gamma-ray spectrogram. Undoubtedly the accuracy of the ^{137}Cs determinations could have been improved if the ^{137}Cs and ^{106}Ru had been separated chemically prior to counting.

In spite of a basic lack of accuracy in all ^{137}Cs determinations, the mass curve for White Oak Creek probably is reasonably accurate.

The outstanding feature of Fig. 5.6 that immediately catches the eye is the extremely great load shown for Centers Ferry in the fall of 1961. Due to a malfunctioning of the sampling equipment here during this period, the reported load is undoubtedly incorrect. If the curve value for December 1, 1961, is adjusted to about 21 curies (the value obtained by extending the curve established prior to about October 1), and if the load thereafter is accumulated from this value, the entire mass curve for this station appears more reasonable and is very similar to that for Gallaher Bridge.

Because of the very limited accuracy of analysis, particularly in the dilute samples collected from the Tennessee River, no detailed discussion of the mass curves for Watts Bar and Chickamauga Dams is warranted.

As explained later in this chapter, appreciable amounts of ^{137}Cs were sorbed and retained in the sediments, especially in the Clinch River embayment.

The affinity of each radionuclide for suspended solids (silt) is shown in Table 5.3. Note here the high percentage of the total ^{137}Cs activity found in the suspended solids.

ACCUMULATION OF RADIONUCLIDES IN CLINCH RIVER BOTTOM SEDIMENTS

Physical and Chemical Characteristics of Bottom Sediments[8]

Composites of the radioactive zones of two cores from CRM 7.5 and CRM 14 had the following average characteristics: 14.2%, sand size; 63.3%, silt size; and 22.5%, clay size ($<2\ \mu$); and an average cation exchange capacity of 12.1 meq/100 g for the silt fraction and 34.1 meq/100 g for the clay fraction. The sand-size fraction consisted of 70 to 80% quartz with smaller amounts of feldspar, dolomite, and mica. The silt-size fraction was 60 to 70% quartz with smaller amounts of mica, mixed layer mica-vermiculite, vermiculite, aluminum-interlayered vermiculite, kaolinite, feldspar, and dolomite. The clay-size fraction contained 10 to 20% quartz with approximately the same amount of mica and kaolinite and smaller amounts of vermiculite, aluminum-interlayered vermiculite, and mixed layer mica-vermiculite. There was about ten times as much organic carbon present as mineral carbon (0.21 and 2.5% by weight). Free iron and aluminum oxides were present at 2.42 and 1.45% respectively. Tamura has shown that these hydrous sesquioxides have exceptionally strong absorptive capacities for strontium, most likely due to the nature of their bonding.[9] The percentages of stable potassium, rubidium, cesium, and strontium present in bottom sediments were 1.84, 0.0097, 0.00042, and 0.0082% by weight respectively.

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[8]R. J. Pickering, *Physico-Chemical Characteristics of Clinch River Bottom Sediment and Their Effect on the Radionuclide Content of the Sediment,* presented at Clinch River Study Steering Committee meeting, December 1964.

[9]T. Tamura, "Selective Ion Exchange Reactions of Cesium and Strontium by Soil Minerals," *Colloq. Intern. Retention Migration Ions Radioact. Sols,* Presses Universitaires de France, 108 Boulevard Saint-Germain, Paris, pp. 95–104 (1963).

Table 5.3. Concentration of Radionuclides at Sampling Stations (curies/liter)

	^{90}Sr			^{106}Ru			^{60}Co		^{137}Cs	
	Flow Weighted Mean Concentration	Maximum Concentration	Mean Activity in Suspended Solids (%)	Flow Weighted Mean Concentration	Maximum Concentration	Mean Activity in Suspended Solids (%)	Maximum Concentration	Mean Activity in Suspended Solids (%)	Maximum Concentration	Mean Activity in Suspended Solids (%)
	$\times 10^{-12}$	$\times 10^{-12}$	$\times 10^{-12}$	$\times 10^{-12}$	$\times 10^{-12}$	$\times 10^{-12}$	$\times 10^{-12}$	$\times 10^{-12}$	$\times 10^{-12}$	$\times 10^{-12}$
Clinch River at Oak Ridge Water Plant (CRM 41.5)	0.71	5.0	24	23	223	44	5	5	6	82
White Oak Creek at White Oak Dam (WOCM 0.6)	1,349	17,450	2	109,800	294,412	6	4,095	19	6,409	69
Clinch River at ORGDP water intake (CRM 14.4)	4.5	11.7	6	345	769	17	18	27	21	92
Clinch River above Centers Ferry (CRM 5.5)	4.2	42.6	9	317	2,633	16	52	30	35	86
Tennessee River at Loudon, Tennessee (TRM 591.4)		2.3			296		1		34	
Tennessee River at Watts Bar Dam (TRM 529.9)	1.6	16.4	9	63	192	7	33	2	18	30
Tennessee River at Chickamauga Dam (TRM 471.0)	1.6	14.1	10	51	269	8	3	3	6	19

Radionuclide Content

To make a total mass balance of radionuclides within the study reach, it was necessary to know the flux of nuclides into and out of the study reach, and the buildup or decline of the radionuclide reservoir within the study reach. Consequently, representative cores of the contaminated sediments in the Clinch River bottom were recovered and analyzed. In 1960 a set of 2-ft cores was taken with a Phleger sampler. Though it was known that the total depth of contaminated sediment had not been sampled, it was estimated that in the top 14 in. of sediment, between CRM 4.7 and CRM 20.8, *76.5 curies* of radioactivity were present: ^{137}Cs, 43.2; TRE, 14.7; ^{106}Ru, 13.2; ^{60}Co, 4.7; and ^{90}Sr, 0.7 curies.[10] At the same time another estimate was made, assuming that the total depth of sediment from CRM 0.0 to CRM 20.8 was uniformly contaminated and that the concentrations were the same as those in the 2-ft cores. Under these assumptions, the estimated total was *1670 curies:* ^{144}Ce-^{144}Pr, 3.3; ^{106}Ru-^{106}Rh, 957.7; ^{137}Cs-^{137}Ba, 609.8; ^{95}Zr-^{95}Nb, 6.5; ^{60}Co, 66.8; ^{90}Sr, 25.6 curies.[11]

Due to the wide difference in these estimates and the admittedly inadequate coring, a more comprehensive coring program was undertaken in 1962 with the Swedish foil sampler.[12] From the results of the analyses of these cores, a total inventory of *200.7 curies* was computed to be in the Clinch River from CRM 0 to CRM 20.8, including the tributaries. The radionuclide content of these cores was as shown in Table 5.4.

The total volume of sediments in the study reach was calculated to be 91×10^6 ft^3. Of this total, 84.8×10^6 ft^3 was estimated to be contaminated. Most of the contaminated sediment was

[10] P. H. Carrigan, Jr., "Inventory of Radioactivity in Bottom Sediments of the Clinch River," presented at Clinch River Study Steering Committee meeting, December 1964.

[11] R. J. Pickering, P. H. Carrigan, Jr., and W. M. McMaster, "Extraneous Sources of Release of Radionuclides to Clinch River," presented at Clinch River Study Steering Committee meeting, December 1963.

[12] R. J. Pickering, "Use of the Swedish Foil Sampler for Taking Undisturbed Cores of River Bottom Sediments," *Proc. Fed. Inter-Agency Sedimentation Conf.*, Jackson, Miss. (Jan. 28–Feb. 1, 1963).

Table 5.4. Radionuclide Content of Cores Obtained from Clinch River

Nuclide	Curies	Percent of Total	Percent of Nuclide Released over White Oak Creek Dam in Sediment[a]
^{137}Cs	154.6	77.0	21
^{60}Co	17.5	8.7	9
^{106}Ru	15.5	7.7	0.4
Total rare earths	10.2	5.1	*b*
^{90}Sr	2.9	1.5	0.2

[a] These values have taken radioactive decay into account.

[b] Not obtained due to the different half-lives and the unknown relative abundance of the various rare earths.

concentrated in the lower reaches of the river, where most of the uncontaminated sediments are also found. Over 81% of the uncontaminated sediment is below CRM 16.9.

To obtain a satisfactory inventory of the radionuclides in bottom sediments, 163 cores were taken at 135 coring sites across 18 sections.[13] Upstream from CRM 13 the sediments were mostly along the banks. Downstream the sediments tend to be thicker and to extend across the entire channel. If deposition of the contaminated sediments took place in a rather uniform manner with time, then it should be possible to correlate the variation in vertical distribution of the gross radioactivity with variations in periodic releases from the Laboratory. A typical river cross section is shown in Fig. 5.7. A computer program was devised to compute the gross radioactive profile from a number of cores. Twenty-seven of the most distinctive cores were compared with the annual ^{137}Cs releases from the Laboratory using appropriate decay factors.[14] The average correlation coefficient was 0.76. The correlation coefficient was improved to 0.80 by adding to it, with the appropriate correction factors for gamma emissions and decay, the annual ^{60}Co releases from the Laboratory.

To further define variation in radioactivity with depth, the gamma spectra of the most radioactive cores were determined. Figure 5.8 shows a typical example of the variation of the concen-

[13] R. E. Blanco and E. G. Struxness, *Waste Treatment and Disposal Progr. Rept. August and September 1961*, ORNL-TM-49 p. 53.

[14] R. J. Morton (ed.) *et al.*, *Status Report No. 5 on Clinch River Study*, Clinch River Study Steering Committee. ORNL-3721, p. 47 (October 1965).

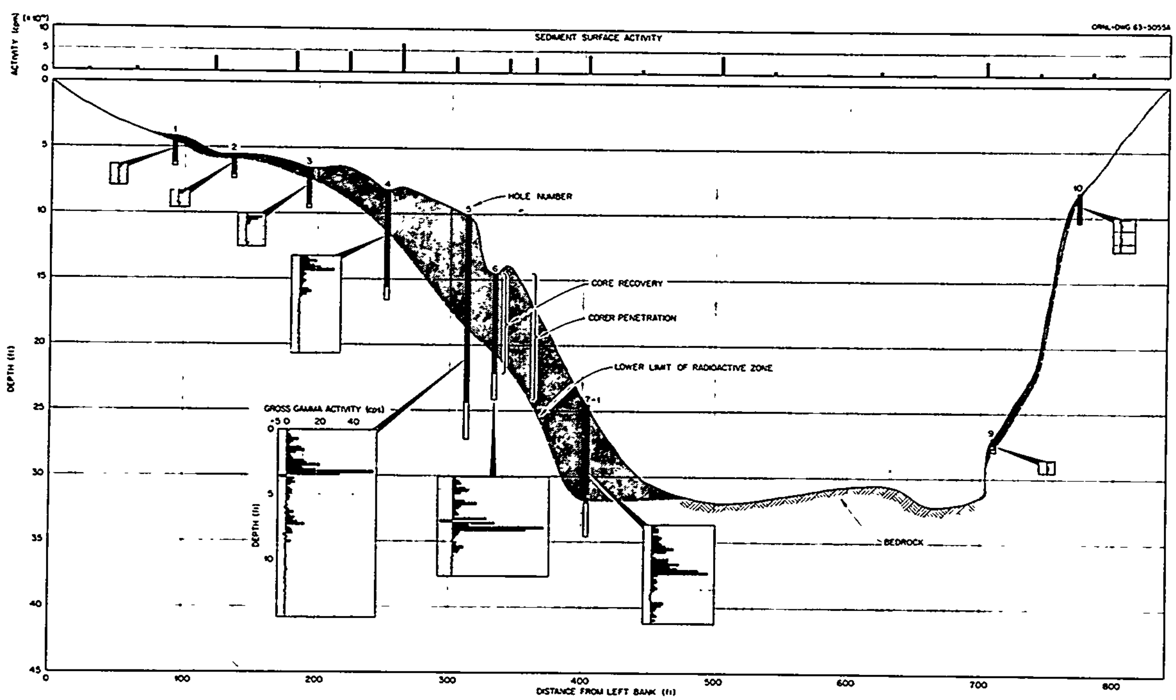

Fig. 5.7. Cross Section at CRM 7.5 Showing Penetration, Recovery, and Gross Gamma Radioactivity Variations with Depth for 1962 Bottom Sediment Core Samples (Vertical Exaggeration 20:1).

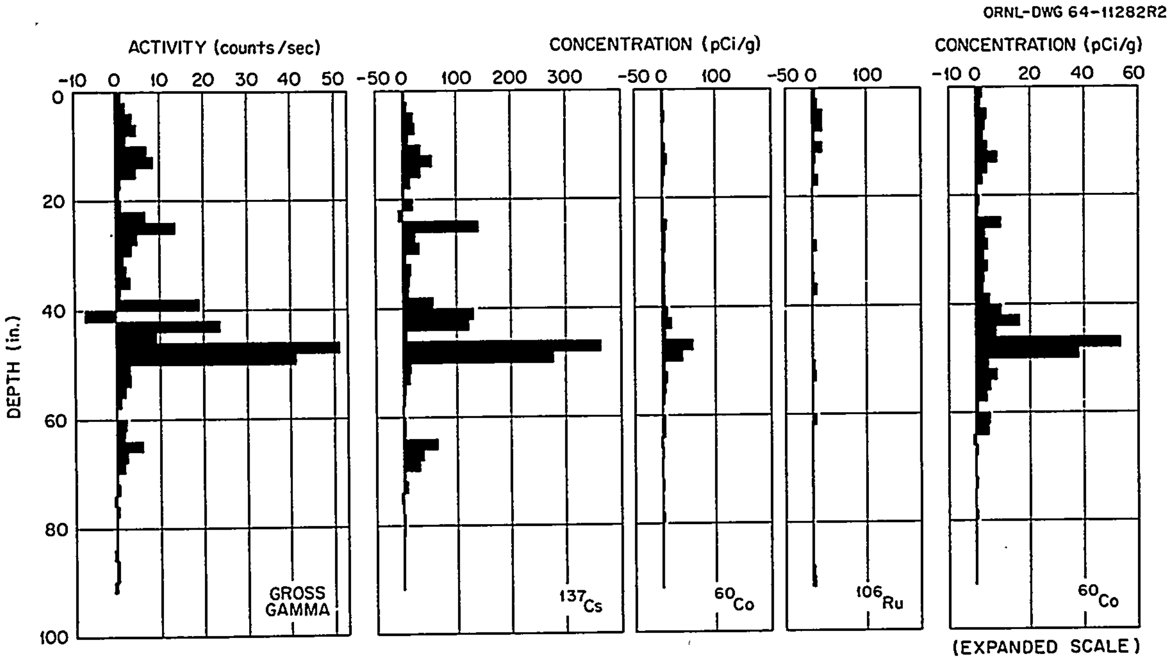

Fig. 5.8. Variations with Depth in Concentrations of ^{137}Cs, ^{60}Co, and ^{106}Ru in Bottom Sediment Core from Hole 6, CRM 7.5.

tration of ^{106}Ru, ^{137}Cs, and ^{60}Co with depth.[15] If it is assumed that the peak gross gamma counts were due to the large release of ^{137}Cs in 1955, when White Oak Lake was drained, then, due to its short half-life, ^{106}Ru should be negligible after the first 10's of inches. The apparent similarity in distribution of ^{137}Cs and ^{60}Co was borne out by a statistical analysis of nine bottom sediment cores where the average correlation coefficient for cesium and cobalt was 0.88. In the nine selected cores 81% of the gross gamma radioactivity was due to ^{137}Cs, 12% to ^{60}Co, and 7% to ^{106}Ru.

The possibility that radioactivity might build up in the sloughs and embayments along the study reach was checked. This might be expected to occur because of the lower velocities involved and the frequent recurrence of algal blooms. "Flounder" measurements showed that the surface radiation in the sloughs was within the range of activities found in the main channel but that the maximum radiation levels in the sloughs were never as high as the maxima in the main channel.[16]

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[15] P. H. Carrigan, Jr., "Inventory of Radioactivity in Bottom Sediments of the Clinch River," presented at Clinch River Study Steering Committee meeting, December 1964.

[16] R. J. Pickering, "Survey of Bottom Sediment Radioactivity in Clinch River Sloughs," presented at Clinch River Study Steering Committee meeting, December 1963.

Desorption of Contaminated Sediment[17]

An intensive study of grab samples of bottom sediment was made to determine the leachability of the nuclides from sediments and to indicate some of the mechanisms which might have caused the sorption of the nuclides. The sediments taken from White Oak Creek contained (dis/min per 50 g, oven-dry basis): $^{103-106}$Ru, 129,000; ^{137}Cs, 118,000; total rare earths, 24,200; ^{60}Co, 16,600; ^{144}Ce, 4150; and ^{90}Sr, 2400. The results of desorption tests are shown in Table 5.5. Leaching by up to 1 *M* solutions of salts between pH 6 and 8 indicate that only ^{90}Sr appears to be held by simple ion exchange and consequently is easily removed. In strongly acid systems (pH = 2) of HNO_3 and HCl, over 65% of the ^{60}Co and over 80% of the ^{90}Sr were desorbed. In strongly alkaline systems (pH $\sim$ 12) of NaOH and NH_4OH, about half of the ^{106}Ru and about 15% of the ^{60}Co were released.

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[17]R. J. Morton (ed.) *et al.*, *Status Report No. 5 on Clinch River Study*, Clinch River Study Steering Committee, ORNL-3721, pp. 52–62 (October 1965).

Table 5.5. Removal of ^{60}Co, ^{137}Cs, ^{106}Ru, and ^{90}Sr from Clinch River Sediment by Various Solutions

50 g (oven dry equivalent) CRM 20.8

400 ml solution, 24 hr contact

Reagent	Concentration (*M*)	pH	Percent Removal			
			^{60}Co	^{137}Cs	^{106}Ru	^{90}Sr
Tap water		6(HNO_3)	2.8	*a*	3.0	21.3
Tap water		2(HNO_3)	64.6	*a*	3.1	80.9
Tap water		1(HNO_3)	78.1	3.3	5.5	
Tap water		6(HCL)	*a*	*a*	3.5	19.4
Tap water		2(HCL)	65.6	*a*	4.1	89.9
Tap water		7.7(natural)	*a*	*a*	4.5	11.0
$NaHSO_3$	0.1	6	16.8	*a*	9.8	37.7
$K_2Cr_2O_7$	0.1	5.6	5.9	1.7	4.7	73.1
$CaCl_2$	0.1	7	6.4	*a*	4.1	58.6
$CaCl_2$	1.0	7	4.7	*a*	4.4	76.9
NaCl	0.1	6	3.5	0.8	4.1	39.2
NaCl	0.1	8	*a*	5.7	6.8	30.1
NaCl	1.0	6	*a*	0.7	3.9	63.1
NaCl	1.0	8	*a*	0.6	5.1	56.0
KCl	0.1	6.2	*a*	0.7	2.8	53.0
KCl	1.0	6.2	3.0	1.7	2.5	68.7
NaOH		8	*a*	0.4	5.9	6.0
NaOH		12	16.5	3.1	46.6	4.9
NH_4OH		8	*a*	0.7	8.2	20.0
NH_4OH		11.8	17.2	4.5	45.1	3.5
Ethyl alcohol					0.9	< 1
Acetone					1.0	

[a]Concentration below detectable limits.

EFFECTS OF MELTON HILL DAM

During the period of the Clinch River Study, TVA began construction of Melton Hill Dam at CRM 23.1, just 2.3 miles upstream from the entry of White Oak Creek into the Clinch River. Since the Melton Hill power station is used to help carry peak power loads, flow releases may be as high as 18,000 cfs. Such high discharges will alter the flow regime considerably. These high flows cause the level of water in the Clinch River to rise rapidly and thus to block the outflow of water from the White Oak Creek embayment for approximately 6 hr each day. At the cessation of power releases, the contaminated White Oak Creek waters are released as a "slug" to the river. River flow conditions differ somewhat between summer and winter, as seen in Table 5.6.

Table 5.6. Comparison of Summer and Winter Flow Conditions in Clinch River

	Summer	Winter
Elevation at Watts Bar, ft	741	735
Stratification	Yes	No
Expected peak of flows from Melton Hill Dam, cfs	16,000	18,000
Weekend flows	No	No
Midday flows	No	Yes

To test the effect of these peaking flows on diffusion of radioactive releases from White Oak Creek, waters were discharged for diffusion test purposes through the gates of Melton Hill Dam, through the cooperation of TVA, to simulate winter and summer conditions. Temperature measurements in the reservoir showed that this water would behave essentially the same as that released through the turbines. Rhodamine B dye was added to the water flowing through White Oak Dam, and movement of the dye in White Oak Creek embayment and in the Clinch River was monitored.[18]

The first dye test, simulating a 24-hr summer weekday release, showed that the dye ponded in the creek embayment during the release of waters from Melton Hill Dam and that the ponded embayment waters were then released during periods of no flow from Melton Hill Dam. Because time of travel in the creek embayment is slow, that is, greater than 24 hr, not all the dye injected in a 24-hr period was flushed out of the embayment in the next 24 hr. The rates of release and concentrations could be estimated by a modified estuary theory for the one-dimensional well-mixed case.[19] The concentrations downstream in the Clinch River could be predicted on the basis of estimated pulsed releases and a one-dimensional transport equation. Eddy diffusion coefficients used in this equation were those computed from previous steady-flow tracer tests. The critical

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[18] R. J. Morton (ed.) *et al.*, *Status Report No. 6 on Clinch River Study*, Clinch River Study Steering Committee, ORNL-3941, pp. 42–58 (November 1966).

[19] P. H. Carrigan, Jr., B. J. Frederick, and F. L. Parker, "Power Release Diffusion Study – Early Spring 1964," presented at Clinch River Study Steering Committee meeting, December, 1964.

case would be the massive transport of accumulated dye (and radionuclides) after a weekend of no releases from Melton Hill Dam. Therefore, dye was added to the water at White Oak Dam for one week each during the simulated summer and winter flow regimes. Predicted values and the results of the 168-hr tests are shown in Table 5.7. Figure 5.9 is a plot of the concentrations measured at CRM 14.4 for the 168-hr test simulating summer releases, compared with predicted concentrations.

The median daily dilution of White Oak Creek waters with Clinch River waters at CRM 20.8 is 570. The minimum dilution factor of White Oak Creek waters at the peak concentration at CRM 14.4 is 54 for summer conditions and 17 for winter conditions. These concentrations persist for only short periods of time. The average percentage of the maximum permissible concentrations of radionuclides in drinking water at the ORGDP water plant intake has been about 2% over the last few years. Since the concentrations can be averaged over a year's time in estimating dose to members of the general public, and the total amount of radionuclides released has not increased, it is felt that no additional hazard has been created by changes in the flow regime produced by Melton Hill Dam.

Table 5.7. Peak Concentrations and Their Times of Arrival at Oak Ridge Gaseous Diffusion Plant

Date (1963)	Summer Flow Conditions: Times of Arrival of Peak		Concentration of Peak (μg/liter)		Date (1964)	Winter Flow Conditions: Times of Arrival of Peak		Concentration of Peak (μg/liter)	
	Observed	Predicted	Observed	Predicted		Observed	Predicted	Observed	Predicted
Aug. 22	1000	0945	4.5	9.1	April 1	1045	1055	25.9	26.9
	1145	1130	5.1	15.5		2056	2100	9.8	8.5
Aug. 23	0945	0945	21.5	21.5[a]	April 2				
	1145	1130	13.0	17.2					
Aug. 24					April 3				
Aug. 25					April 4	1044	1055	51.3	53.0
						2049	2100	13.8	11.0
Aug. 26	0945	0945		22.6	April 5	1049	1055	22.9	15.9
	1145	1130	45.0	42.7					
Aug. 27	1000	0945	34.2	41.2					
	1130	1130	17.0	22.5					
Aug. 28	1000	0945	22.5	25.0					
	1145	1130	14.0	18.0					
Aug. 29	1000	0945	12.1	14.9					
	1145	1130	7.7	4.2					
Aug. 30		0945		1.1					
		1130		0.4					

[a]Values normalized about this point.

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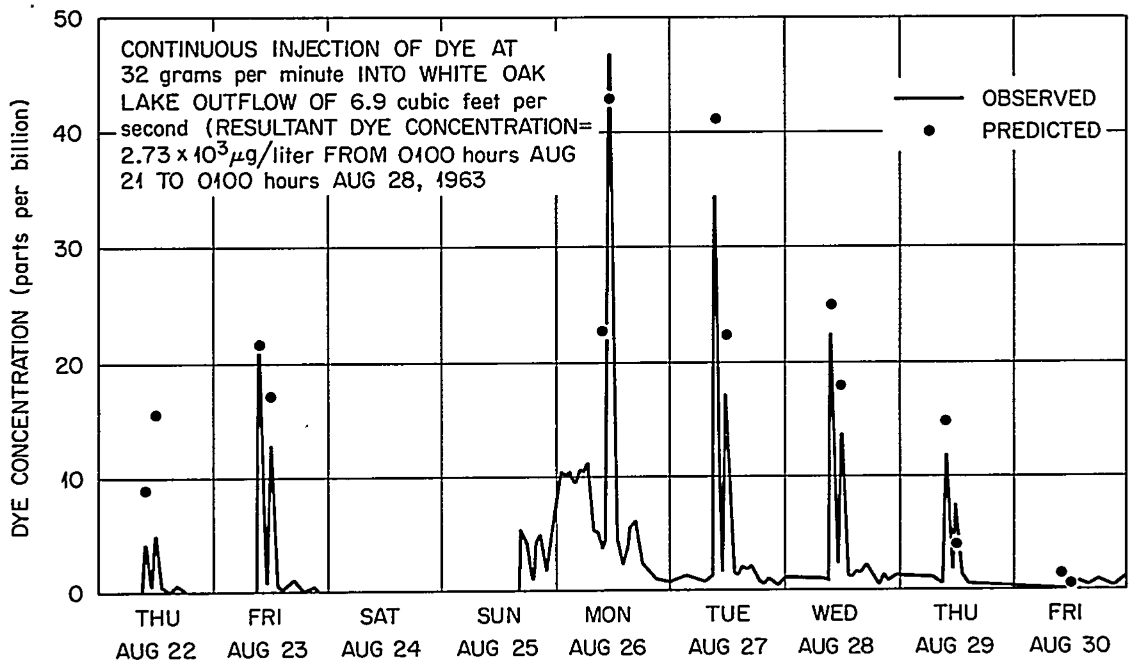

Fig. 5.9. Observed and Predicted Variation in Rhodamine B Concentration with Time During Period August 22–30, 1964, at Clinch River Mile 14.4.

COMPUTER SIMULATION OF RADIOACTIVE WASTES IN STREAMS

Simulation studies of pollutant-stream systems by the use of a mathematical model that represents stream characteristics and pollutant loadings are necessary because of the multiple interdependences between hydrologic parameters and pollutant input variables. Simulation extends the range of experimental data by varying important parameters in the model.

This mathematical model[20] was developed as a stochastic process (process in which at least one of the variables in the system is a random variable or has an element of randomness) and simulates the physical processes and interactions of stream flow, dilution, mixing, nuclear decay, uptake and release from benthal deposits, water withdrawal at use points, and water treatment (Fig. 5.10). Based upon the data developed during the Clinch River Study, representative values for the Clinch and Tennessee Rivers as a function of increasing flow; of deposition, y_2/y_1 (0.40 to 0); scour or leaching, y_3/Y (0 to 0.25); time of travel (decay), $y_4/(y_1 - y_2)$ (0.002 to 0); and treatment plant efficiencies, y_6/y_5 (0.35 to 0.15) were used. The flow in the river, x_1, is generated by sampling from a population defined by a Markov chain. Markov chains are the

[20] H. A. Thomas, Jr., and M. B. Fiering, "A Model for Computer Simulation of the Fate of Radioactive Wastes in Streams," *Operations Research in Disposal of Liquid Radioactive Wastes in Streams (Part V)*, NYO-10447 (December 1965).

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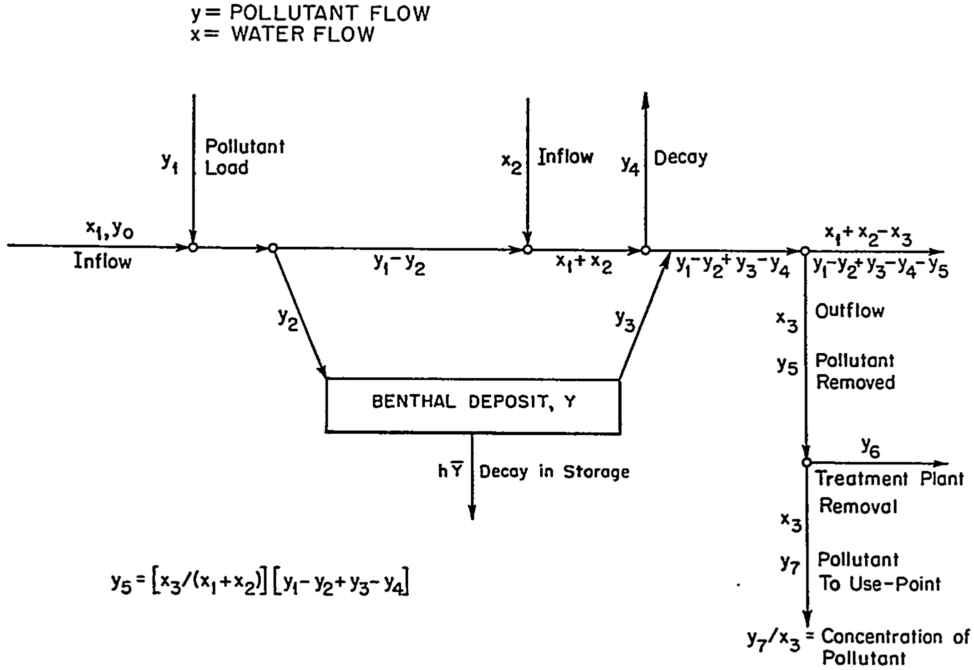

Fig. 5.10. Vector Diagram Flow of Water and Pollutant.

simplest generalization of a scheme of independent trials. The additional input data, such as inflow, x_2; outflow, x_3; and pollutant loads, y_0 and y_i, are assumed to be dependent only on x_1 and are generated from a recursion formula. The average flows and withdrawals in the Clinch and Tennessee Rivers and the contaminant inputs were derived for a 200-year period with results as shown in Table 5.8. With this input data and an absolute value for the decay constant, h, the variables of interest – the average, maximum, and minimum curie loads and concentrations at the use points and in the benthal deposits – could be computed. The program was run on the computer for a four-season model (i.e., treating each successive three months as a season) for the Clinch and Tennessee Rivers, as other studies showed that the annual model was not sufficiently representative.

The effect of variation in the input parameters (flow, pollutant, etc.) upon the pollutant concentration at the use points is shown in Table 5.9. It should be noted that the effect of drastically decreasing the standard deviation of the pollutant input while still maintaining the same mean input is quite small. The effect on the range of the values, however, is marked. For the Clinch River (run 10), where 200% of the standard deviation of the pollutant input was used, the mean activity loading is 1.17 mc and the maximum is 5.33 mc; and at 0 standard deviation (run 12) the mean is 1.51 mc and the maximum loading is 1.81 mc. The mean and maximum loadings for the Tennessee River as shown in run 2 for 200% standard deviation of pollutant input are 11.34

Table 5.8. Input Data for Four-Season Model of Clinch and Tennessee Rivers

Season	Flow (cfs)		Withdrawal (cfs)		Contaminant Input (curies)		Fallout Input (curies)	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
				Clinch River				
1	1,488	750	0.19	0.06	4.28	3.94		
2	783	324	0.22	0.07	2.25	2.07		
3	1,052	246	0.28	0.08	1.97	1.81		
4	1,309	392	0.19	0.06	1.50	1.38		
Annual	4,632	1,119	0.88		10.00			
				Tennessee River				
1	12,508	3,334	14.66	4.36	4.28	3.94	7.94	3.92
2	6,825	1,197	16.56	4.92	2.25	2.07	10.20	5.81
3	6,925	1,074	20.59	6.04	1.97	1.81	9.03	4.52
4	8,827	2,741	14.66	4.36	1.50	1.38	8.64	3.97
Annual	35,085	5,572	66.46		10.00		35.81	

and 53.42 mc, and in run 4 for 0 standard deviation, 13.9 and 15.5 mc respectively. Such great variability in the pollutant input when the mean input remains the same has only a minor effect upon the mean intake.

Runs 5 and 13 are the deterministic models (standard deviations of all input variables were set at zero), and, again, the effect on the mean values is small. In systems where the contaminant input differs greatly in time from the stream flow input and the contaminant removal, the range of the means could be greater.

The effect of the elimination of the benthal deposits and the filter plant is shown in run 6. If 25% reduction is allowed in the expected load due to the treatment plant, there is still a slight increase in the intake loading. This is due to the amount taken up and decayed in the benthal deposits, as well as the part that may be due to stochastic components of the input variables.

The most important information derived from the simulation of the Clinch-Tennessee River system was that the mean concentrations at the critical points are only slightly affected by a wide range of pollutant inputs and flows provided the mean inputs are constant. Moreover, the system must be studied by a model with time periods no greater than three months. The simulation program as developed could be used, with additional economic input, to determine the optimum place and time to treat the wastes discharged from the Laboratory.

Table 5.9. Intake Concentrations Due to Variation of Parameters

Run No.	Contaminant Input (Percent of Standard Deviation)	Flow - Input (Percent of Standard Deviation)	Benthal Removal (%)	Filter Plant Removal (%)	Fallout Input (%)	Expected Load per Year (mc)	Maximum Load per Season (mc)	Expected Conc. per Year (pc/liter)	Maximum Conc. per Season (pc/liter)	Benthal Deposits (curies)
					Tennessee River					
1	100	100	100	100	0	12.12	21.65	0.2151	1.5780	1.668
2	200	100	100	100	0	11.34	53.42	0.2085	4.6610	1.398
3	50	100	100	100	0	12.79	14.72	0.2207	0.7805	1.897
4	0	100	100	100	0	13.87	15.52	0.2306	0.5284	2.220
5	0	0	100	100	0	13.61	4.04	0.2306	0.3081	1.381
6	100	100	0	0	0	17.48	40.06	0.3056	2.149	0.000
7	100	100	100	200	0	8.03	17.83	0.1385	0.8156	1.6682
8	100	100	100	100	100	59.79	53.03	1.0563	3.698	9.662
					Clinch River					
9	100	100	100	100	0	1.28	2.232	1.6929	12.050	2.064
10	200	100	100	100	0	1.17	5.325	1.6082	32.020	1.715
11	50	100	100	100	0	1.38	2.189	1.7648	7.570	2.398
12	0	100	100	100	0	1.51	1.807	1.8813	5.476	2.945
13	0	0	100	100	0	1.37	0.432	1.7794	2.569	1.368
14	100	100	100	200	0	0.85	1.812	1.0902	8.036	2.064

6. Uptake, Cycling, and Effects of Radionuclides in Clinch-Tennessee River Biota

Biota living in a contaminated river affect the distribution of radionuclides in a minor way and, in turn, may be affected by the ionizing radiation. The extent of these interactions and the consequent effects on humans and on utilization of this natural resource depend largely upon the levels of radioactivity involved and the extent of radionuclide concentration by biota. In a stream ecosystem there are complex pathways in the food chain by which radioactive wastes may reach man. Fortunately, it is seldom necessary to define or describe each link of the food chain to assess the consequences. Because fish are the major human food sources derived from the Clinch and Tennessee Rivers, knowledge of the fish in relation to radioactive contamination is essential.

FISH POPULATIONS

Fish tagging studies provided data on the species of fish in the Clinch River (Table 6.1) and their movements in relation to White Oak Creek embayment (Fig. 4.1). Fish movements in the vicinity of White Oak Creek to adjoining portions of the Clinch-Tennessee River were inferred from the location of the recoveries of tagged fish.

There were 317 (6.05%) recoveries from 5244 fish tagged (Table 6.1). Most of the recoveries were of white bass and white crappies, two of the most commonly caught fish. The white bass were originally captured as they made an upstream spawning run in the Clinch River during April and May and then were recaptured by fishermen after they returned to Watts Bar Reservoir. The distance between the points of tagging and recovery of white bass ranged from 0 to 130 river miles; the average distance was 33.4 miles. The average time between tagging and recovery was 65 days. White crappies were recovered largely by ORNL netting operations. While individual fish were recovered from 0 to 60 miles from the point of tagging, the average distance between points of tagging and recovery was only 11.9 river miles. The average time between tagging and recovery was 144.3 days.

These comparative data on the migratory habits of white bass and white crappie, obtained early in the Clinch River Study, reveal two points of immediate interest. First, white crappies do not, as a rule, move around to any great extent in the Clinch River. Thus the white crappie

Table 6.1. Species and Numbers of Fish Tagged and Numbers of Fish-Tag Returns

	Number Tagged	Tag Returns	Percent Returns
Longnose gar, *Lepisosteus osseus*	3		
Skipjack herring, *Alosa chrysochloris*	30	3	10
Gizzard shad, *Dorosoma cepedianum*	577	10	1.73
Mooneye, *Hiodon tergisus*	12	1	8.33
Carp, *Cyprinus carpio*	978	12	1.23
River carpsucker, *Carpiodes carpio*	183	13	7.10
Quillback, *Carpiodes cyprinus*	11		
Smallmouth buffalo, *Ictiobus bubalus*	639	17	2.66
Bigmouth buffalo, *Ictiobus cyprinellus*	1		
Black buffalo, *Ictiobus niger*	6		
River redhorse, *Moxostoma carinatum*	2		
Black redhorse, *Moxostoma duquesnei*	1		
Golden redhorse, *Moxostoma erythrurum*	94	7	7.45
Blue catfish, *Ictalurus furcatus*	24	3	12.5
Yellow bullhead, *Ictalurus natalis*	2		
Channel catfish, *Ictalurus punctatus*	151	17	11.26
Flathead catfish, *Pylodictis olivaris*	10		
White bass, *Roccus chrysops*	812	157	19.33
Rock bass, *Ambloplites rupestris*	6		
Bluegill, *Lepomis macrochirus*	149		
Longear sunfish, *Lepomis megalotis*	2		
Smallmouth bass, *Micropterus dolomieui*	2	1	50.00
Spotted bass, *Micropterus punctulatus*	2		
Largemouth bass, *Micropterus salmoides*	5		
White crappie, *Pomoxis annularis*	1027	59	5.74
Black crappie, *Pomoxis nigromaculatus*	9	1	11.11
Walleye, *Stizostedion v. vitreum*	1	1	100.00
Sauger, *Stizostedion canadense*	42	6	14.29
Freshwater drum, *Aplodinotus grunniens*	463	9	1.94
	5244	317	6.05

is a good species to sample for information on fish continuously exposed to radioactivity in the Clinch. Second, prior to the construction of Melton Hill Dam there was little sports fishing on the Clinch River. This is indicated by the fact that most tag returns of white bass were by sportsmen on Watts Bar Reservoir, in contrast to ORNL's recoveries of white crappie tags on the Clinch.

Radioactive Scales

During a study of smallmouth buffalo populations in the Clinch and Tennessee Rivers, another method of detecting fish movements was developed.[1] Fish are free to enter White Oak Creek em-

[1]R. E. Martin, S. I. Auerbach, and D. J. Nelson, *Growth and Movement of Smallmouth Buffalo, Ictiobus bubalus (Rafinesque), in Watts Bar Reservoir, Tennessee*, ORNL-3530 (Jan. 6, 1964).

bayment, below White Oak Dam (Fig. 4.1), and then return to the Clinch River. It was hypothesized that fish living in the embayment would deposit radioactive rings in bony scales and, after leaving, retain the radioactive rings because of slow metabolic turnover. To test this hypothesis, scales were counted for gross beta activity, and those having sufficient activity were placed on no-screen x-ray film for autoradiography.

Eleven fish were found to have sufficient activity to produce autoradiograms (Fig. 6.1). Of these, eight were captured in White Oak Creek embayment, two from the Clinch River (at CRM 21.7 and CRM 16.0), and one from TRM 542. One hundred forty-six smallmouth buffalo from the Clinch River were tested for radioactive rings, as were 1271 fish from Watts Bar Reservoir below the mouth of the Clinch.

Since radioactive rings in fish scales may be associated with growth, movements of the fish were related to age and growth of the fish. In the 11 fish studied autoradiographically, there were 16 indications of movement between White Oak Creek and the river. Twelve moves coincided with the resumption of growth at the time of annulus formation. This would indicate that the majority of moves occurred during late winter or early spring. Quantitatively, smallmouth buffalo movement between White Oak Creek embayment and the river did not appear to be significant, because only a small portion of the population examined had radioactive rings.

Radioactive rings in fish scales provided a continuum of information relating the fish to higher concentrations of environmental radioactivity in the White Oak Creek embayment. Because of the continuous record, this technique was superior to conventional tagging methods, which would indicate only when the fish were tagged initially and when they were later recovered.

Strontium-90 in White Crappies

When the distribution of stable strontium between fish tissue and water is known, it should be possible to predict the consequent ^{90}Sr burdens in fish for any specified, continuous release of ^{90}Sr to the river. Furthermore, with a knowledge of the biological half-life of strontium in fish tissues it should be possible to predict the tissue concentrations for transient conditions when releases vary with time.

Fish tagging investigations showed that white crappies had a relatively small home range. Therefore it was anticipated that these fish collected from the Clinch River were exposed chronically to the low-level releases of ^{90}Sr. Under these conditions the same proportions of ^{90}Sr and Sr should occur in fish tissues and in the river water. This simple relationship does not take radioactive decay into account, but the error introduced would be slight because the life of the fish is short compared with the half-life of ^{90}Sr.

Calcium and strontium concentrations in white crappie flesh and bone were constant throughout the year, and the average annual concentrations are reported in Table 6.2. Relatively constant calcium and strontium concentrations were expected in bone, because this tissue in fish is

Fig. 6.1. Radioactive Ring in a Smallmouth Buffalo Scale. The fish hatched in the spring of 1957 in a noncontaminated area. It entered a contaminated area immediately after formation of its second annulus, probably in the spring of 1959. The fish remained in the contaminated area until some time during the winter of 1959–1960 and lived in the noncontaminated area until it was captured June 29, 1962, at CRM 16.0.

Table 6.2. Calcium and Strontium Concentrations in White Crappie Flesh and Bone and Clinch River Water[a]

	Number of Samples	Ca	Concentration Factor[b]	Sr	Concentration Factor[b]
White Crappie					
Flesh (μg/g)	113	135 ± 2.43	5.0	0.069 ± 0.035	1.00
Bone (mg/g)	105	365 ± 7.77	13,519	0.268 ± 0.064	3884
Clinch River water (μg/g)		27.0 ± 5.2		0.069 ± 0.0076	

[a]All values ±1 standard deviation.

[b]Concentration factor = concentration per g of tissue/concentration per ml of water.

a biogeochemical sink. Krumholz[2] reported concentration factors of 20,000 for ^{90}Sr in bone of black crappie and 30,000 in bluegill bone. These concentration factors appear high, because stable strontium in white crappie bone was concentrated by a factor of only 4000. Stable strontium and radiostrontium would be expected to have approximately the same concentration factor. The constant concentrations of calcium and strontium in flesh probably reflect the relative constancy of these elements in Clinch River water (Table 5.2). Of particular interest was the fact that the average concentration of strontium in fish flesh was essentially the same as that of river water.

To test whether the specific activity ratios of ^{90}Sr in fish tissue were related to those in water, the specific activity of crappie bone was compared by the proportion

$$\left(\frac{^{90}\mathrm{Sr}}{\mathrm{Sr}}\right)_{\mathrm{water}} = \left(\frac{^{90}\mathrm{Sr}}{\mathrm{Sr}}\right)_{\mathrm{bone}} ,$$

$$\frac{4.3 \times 10^{-3}\ \text{picocurie/ml}}{6.9 \times 10^{-2}\ \mu\text{g/ml}} = \frac{1.446 \times 10^{1}\ \text{picocuries}/\mu\text{g}}{2.68 \times 10^{2}\ \mu\text{g/g}} ,$$

$$6.23 \times 10^{-2}\ \text{picocurie}/\mu\text{g} = 5.39 \times 10^{-2}\ \text{picocurie}/\mu\text{g} .$$

There is relatively good agreement between specific activities in fish bone and water. These data suggest that for any constant release of ^{90}Sr to the river, it is possible to predict the consequent ^{90}Sr content of fish bone or other tissues. Initially, it had been thought that the same proportion might be used to compare ^{90}Sr concentrations in fish flesh with ^{90}Sr concentration in water, but subsequent estimates of the biological half-life indicated this was not advisable.

[2]L. A. Krumholz, "Observations on the Fish Population of a Lake Contaminated by Radioactive Wastes," *Bull. Am. Museum Nat. Hist.* 110(4), 283–367 (1956).

Investigation of the biological half-life (T_b) of ^{90}Sr and ^{137}Cs in fish yielded information of the mode of uptake of these radionuclides. In T_b studies the organisms were tagged with radioactivity, placed in a noncontaminated environment, and loss of radioactivity due to excretion was measured by counting them periodically. Aquatic organisms may accumulate radioactivity from either food or water, or both. The first attempts to induce intake of ^{137}Cs by fish with the radiocesium in aqueous solution were failures. Subsequent experiments in which the fish were fed food contaminated with radiocesium were successful. These experiments showed that fish would obtain their ^{137}Cs burdens via the food chain. The biological half-life of cesium in bluegills was approximately 40 days. This T_b is similar to that observed for cesium in brook trout,[3] but somewhat shorter than that observed in carp.[4]

The T_b of strontium in white crappies was determined by using the gamma emitter ^{85}Sr, which simplified whole-body counting procedures. Attempts to induce uptake in fish with contaminated food were unsuccessful, and further experimentation showed that strontium uptake was directly from the water. Ophel and Judd[5] observed similar results with goldfish and showed that the gills were the primary site of strontium exchange between the fish and its environment.

Measurement of the turnover time of strontium in fish flesh was complicated by the rapid deposition and high concentration of strontium in fish bone, which literally masked the strontium in soft tissues. This difficulty was circumvented by constructing a special excretion tank, which could be inserted in the detector chamber of a counter (Fig. 6.2). Experimental fish were tagged by placing them in ^{85}Sr solutions for 15 min; they were then rinsed, placed in the special excretion tank, and counted at 1-min intervals. Water was pumped through the tank to remove excreted ^{85}Sr and to provide a supply of oxygenated water. Influent water was directed toward the head of the fish. The fish oriented itself toward the current and maintained a constant position with respect to the scintillation detector, resulting in consistent counting geometry. Biological half-lives of strontium determined in this manner ranged from 12 to 48 min, somewhat shorter than had been anticipated.

Because of the short biological half-life of strontium in fish flesh, the planned use of specific-activity ratios to predict ^{90}Sr burdens in the flesh of white crappies was not valid unless accompanied by an ^{90}Sr analysis of river water taken at the same time. The distribution of ^{90}Sr and Sr between tissue and water could be compared only in bone, which acts as an integrating sampler of ^{90}Sr. Furthermore, since the concentration of ^{90}Sr in fish flesh reflects quickly the ^{90}Sr concentration in water, and there is no concentration of strontium in the flesh, it would be advantageous to sample the water instead of the fish. This procedure would be important in assessing the possible hazard associated with peaking power operations at Melton Hill Dam. It might be

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[3]D. P. Scott, "Radioactive Cesium as a Fish and Lamprey Mark," *J. Fisheries Research Board Canada* 19(1), 149–57 (1962).

[4]N. R. Kevern, *Biological Half-Life of ^{134}Cs in Carp and Two Aquatic Insects*, ORNL-3697 (October 1964), pp. 101–2.

[5]I. L. Ophel and J. M. Judd, "Accumulation of Radiostrontium by the Gills of Freshwater Fish," *Nature* 194(4834), 1187–88 (1962).

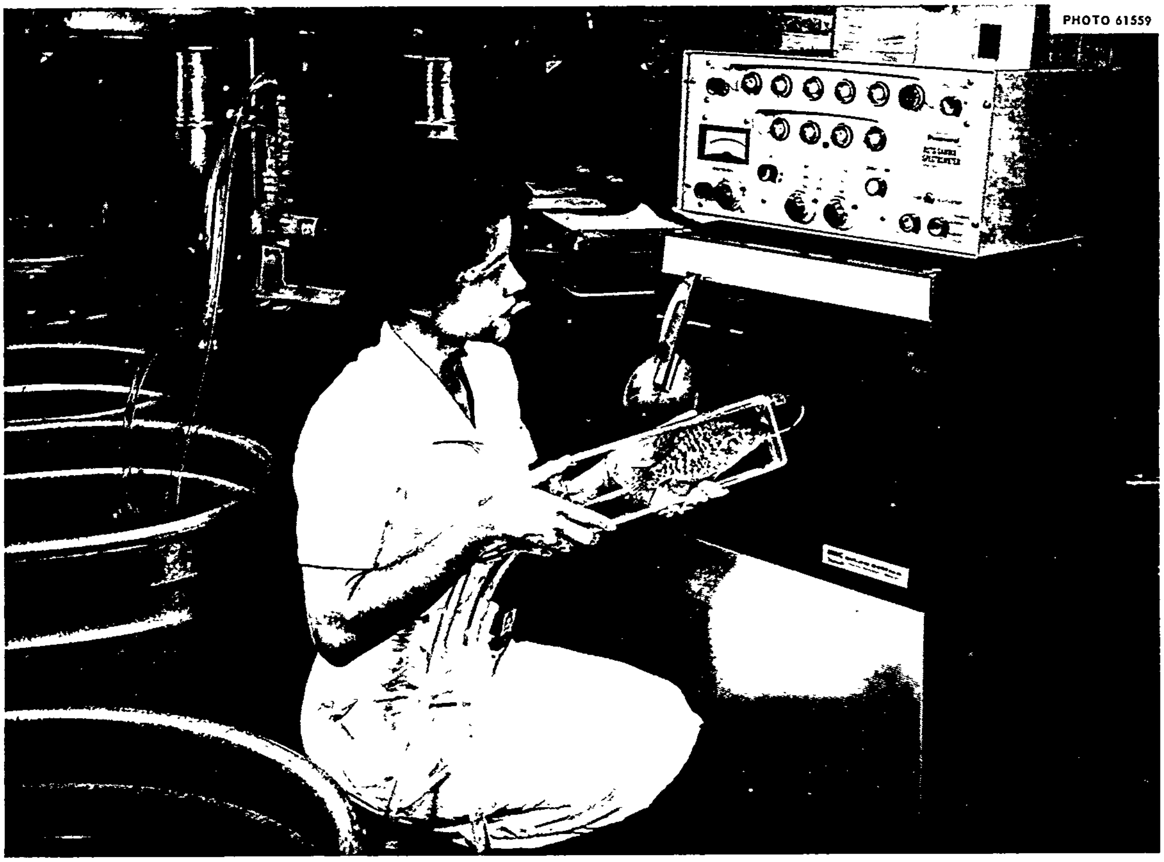

Fig. 6.2. Whole-Body Counter and Fish-Holding Assembly Used in the Measurement of the Biological Half-Life of ^{85}Sr in White Crappie Flesh. Water is pumped through the fish holder via the plastic tubing.

possible to use hydrological data to determine the expected maximum concentrations of ^{90}Sr in the Clinch River near the mouth of White Oak Creek. With knowledge of the expected ^{90}Sr concentrations in water and the short T_b of strontium in fish flesh, ^{90}Sr concentrations in fish flesh should be approximately the same as those in the water.

Contaminated Fish as Man's Food

Estimates of man's intake of radionuclides (Chap. 7) from contaminated fish were based on the analysis of fish by the USPHS in 1960–61 and the cooperative efforts of ORNL and the USPHS in 1962–63. Fish were analyzed individually and data were composited by species for the commercial food species (carp, carpsuckers, smallmouth buffalo) and by group for the game fish (white crappie, bluegill, white bass, largemouth bass, sauger, drum, and channel catfish). Separate collections and analyses were made of Clinch River fish (Table 6.3) and Tennessee River fish (Table 6.4).

Table 6.3. Concentration of Radionuclides in Clinch River Fish
(picocuries per kg of fresh weight)

Fish Species	Sample Period	^{90}Sr Flesh	^{90}Sr Total[a]	^{137}Cs Flesh	^{137}Cs Total[a]	^{106}Ru Flesh	^{106}Ru Total[a]	^{60}Co Flesh	^{60}Co Total[a]
Carp	1960–1962	(17)[b] 500 ± 140[c]	(40) 5100 ± 1700	(71) 510 ± 57	(39) 560 ± 79	(69) 170 ± 18	(39) 290 ± 78	(67) 66 ± 6.1	(39) 49 ± 9.9
	1963	(20) 91 ± 22		(20) 320 ± 110					
Carpsucker	1960–1962	(18) 540 ± 190	(39) 940 ± 120 (39) 4800[d]	(122) 1200 ± 460	(37) 640 ± 67	(22) 120 ± 30	(37) 56 ± 16	(22) 120 ± 19	(37) 32 ± 6.8
	1963	(20) 22 ± 4.4		(20) 460 ± 82					
Buffalo	1960–1962	(3) 240 ± 89	(30) 830 ± 110	(5) 480 ± 94	(30) 590 ± 92	(5) 110 ± 32	(30) 150 ± 38	(5) 78 ± 21	(30) 32 ± 6.8
	1963	(20) 43 ± 14		(21) 560 ± 84					
Sight feeders[e]	1960–1962	(109) 180 ± 83		(126) 680 ± 120		(127) 120 ± 32		(127) 22 ± 11	

[a]Total fish consists of flesh and bone.
[b]Parenthetical values are numbers of fish analyzed.
[c]± values represent 1 standard deviation.
[d]Includes four carpsuckers (composited) collected at CRM 19.6.
[e]Sight feeders include white crappie, bluegill, white bass, largemouth bass, sauger, drum, and catfish.

Table 6.4. Concentration of Radionuclides in Flesh of Tennessee River Fish (picocuries per kg of fresh weight)

Fish Species	Sample Period	^{90}Sr	^{137}Cs	^{106}Ru	^{60}Co
Carp	1960–1962	(13)[a] 120 ± 33[b]	(14) 180 ± 55	(14) 80 ± 27	(14) 71 ± 17
	1963	(20) 5.1 ± 0.75	(19) 61 ± 17		
Carpsucker	1960–1962	(10) 99 ± 28	(10) 130 ± 27	(10) 69 ± 23	(10) 62 ± 18
Buffalo	1963	(20) 8.9 ± 2.9	(20) 73 ± 12		
Sight feeders[c]	1960–1962	(24) 250	(24) 170	(24) 48	(24) 66

[a]Parenthetical values are numbers of fish analyzed.

[b]± values represent 1 standard deviation.

[c]Sight feeders include white crappie, bluegill, white bass, largemouth bass, sauger, drum, and catfish.

Table 6.5. Commercial Fish Harvest from Watts Bar Reservoir and East Tennessee (1962) (pounds of fresh weight)

Location	Carpsucker	Carp	Smallmouth Buffalo
Watts Bar Reservoir	15,600	23,700	161,000
East Tennessee	61,700	135,000	327,000
Fish dilution factor[a]	3.95	5.70	2.03

[a]Fish dilution factor = pounds of East Tennessee fish/pounds of Watts Bar fish.

The large differences in ^{90}Sr concentrations between flesh samples and total fish reflect the higher concentrations in bone. Inclusion of bone in samples obviously represents an extreme maximization of the possible ^{90}Sr intake by humans. A survey of 80 local fishermen, conducted during the summer of 1964, showed that none of them consumed fish in a manner that would include the entire skeleton. Fish consumption by commerical fishermen, assumed to be a high-exposure group, is approximately 37 pounds per person per year.[6] Estimates of radionuclide intake (Chap. 7) were based on the concentration of radionuclides in fish and the annual consumption of fish. Since commercial food fish from Watts Bar Reservoir are mixed and marketed with similar fish from other east Tennessee reservoirs, a fish dilution factor (Table 6.5) was applied to the estimated radionuclide intake by the general population.

[6]P. Bryan and C. E. White, "An Economic Evaluation of the Commercial Fishing in the TVA Lakes of Alabama During 1956," *Proc. 12th Ann. Conf. SE Assoc. Game and Fish Comm.* 12, 128–32 (1958).

CLAMS

When releases of ^{90}Sr from the Laboratory are diluted in the Clinch River, sampling and detection require sophisticated equipment. On the other hand, organisms which concentrate specific radionuclides can be useful indicators of radioactive contamination in the environment. It was hypothesized that ^{90}Sr would be concentrated in the shells of freshwater clams (Unionidae), since the shells contain significant concentrations of stable strontium.[7]

The strontium content of 190 shells representing 15 species ranged from 150 to 550 ppm and varied with the species, age of individuals within a species, and shell growth rate. Clamshell is essentially pure $CaCO_3$ which should yield 40% Ca; the analyses showed 400.9 ± 1.38 mg of Ca per g of shell. These analyses of strontium and calcium in shell showed that conventional $^{90}Sr/Ca$ ratios were not applicable because of the differences in stable strontium concentrations (affecting ^{90}Sr content) and the constancy of the calcium concentrations. However, by using the specific activity of ^{90}Sr to interpret the data, it should be possible to compensate for the difference in stable strontium concentrations.

Biological Indicators

Clams, because of their habits and behavior, should be excellent organisms with which to study the behavior of ^{90}Sr in the environment. They would be expected to assimilate and deposit stable strontium and ^{90}Sr atoms in their shells in the same proportion as these atoms occur in water. The shell is deposited in distinct annual layers which are not subject to subsequent metabolism; consequently, the shell represents a history of the deposition of strontium. Because clams are relatively immobile on the river bottom,[8] their ^{90}Sr content should be representative of the water quality in that section of the river. Clams pump water through their siphons most of the year and, therefore, can be considered as integrating water samplers.

Although clams may live 30 or more years, none of those sampled and analyzed lived in the river prior to 1943. The age of the clams was estimated by the annual ring method.[9] In addition, batches of clams of similar age distribution were selected in order to minimize the effects of radioactive decay and variations in specific activity of the water.

Laboratory releases of ^{90}Sr were considered as a tracer, and the specific activity of ^{90}Sr in clamshells was used to interpret the behavior of ^{90}Sr released to the river system. This treatment of the data was dependent upon (1) the concentration of ^{90}Sr by clams, (2) the determination of the specific activity of ^{90}Sr by stable-chemical and radiochemical analyses, (3) the dilution factors for contaminated water by uncontaminated water at clam collection sites, and (4) the determination of stable strontium content in river water. Clam samples were taken up-

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[7] H. T. Odum, "Biogeochemical Deposition of Strontium," *Institute of Marine Sci.* 4(2), 38–114 (1957).

[8] F. B. Isely, "Experimental Study of the Growth and Migration of Freshwater Mussels," *U.S. Bur. Fish Doc. 792*, 24 pp. (1914).

[9] H. H. Haskin, "Age Determination in Mollusks," *Trans. N.Y. Acad. Sci.* 16, 300–304 (1954).

stream from White Oak Creek (CRM 47, control point), immediately downstream from White Oak Creek (CRM 4.7-17, index point), and at three other downstream locations (Fig. 6.3). The control point was used to evaluate fallout ^{90}Sr, and the index point was used as the basis for interpreting data from other downstream sampling locations.

When ^{90}Sr is released to the river, a specific activity is established with stable strontium in the water mass passing the creek outlet at the time of release. Temporal changes in specific activity of the water mass may result either from the release of different amounts of ^{90}Sr or because of a variation in the strontium content of river water. By relating uptake data to an index, temporal changes in the specific activity may be ignored. Specific activity of the water mass at downstream locations is changed by further dilution of the contaminated water by uncontaminated water and at the confluence of tributary streams having different strontium concentrations. In these instances it is possible to correct the specific activity of the water for dilution of ^{90}Sr and for differences in the concentration of strontium. Specific activity is corrected for dilution by using U.S. Geological Survey river discharge data.[10] The strontium contents of the Clinch and Tennessee River waters are not greatly different (Table 5.2); hence no correction for this factor need be made in this case.

[10] J. S. Cragwall and E. P. Mathews, personal communication.

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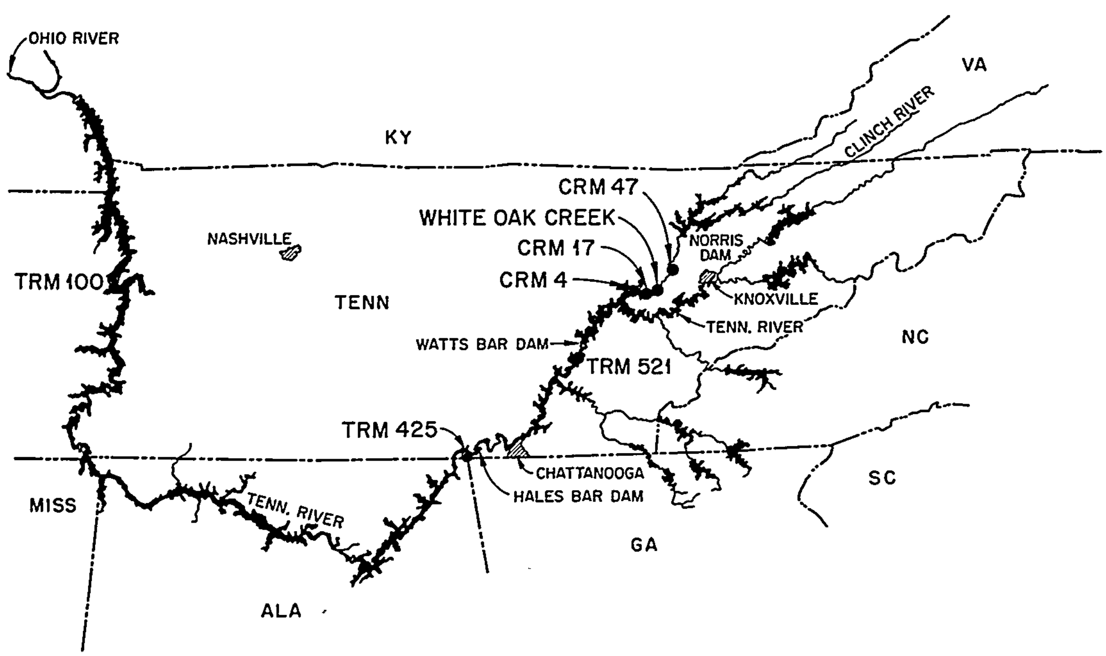

Fig. 6.3. Tennessee River Drainage, Showing the Location of Clam Collection Sites.

The accrual of fallout ^{90}Sr to river water is dependent largely on runoff.[11] Fallout in the region of the Tennessee River drainage is uniform;[12] therefore a constant addition of fallout to the river may be expected.

The behavior of ^{90}Sr in the Clinch and Tennessee Rivers was inferred by comparing the specific activity of ^{90}Sr in clamshells from downstream locations with that of samples from the index point (Table 6.6). Since specific activity in the shells, as predicted solely from the downstream dilution, was approximately the same as the observed activity, the ^{90}Sr loss from the river water might be considered negligible, and it might be assumed that the living and nonliving components of the stream ecosystem are in equilibrium with both ^{90}Sr and stable strontium. Ap-

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[11] A. Morgan and D. G. Stanbury, "The Contamination of Rivers with Fission Products from Fallout," *Health Phys.* 5(3/4), 101–7 (1961).

[12] E. P. Hardy, Jr., *et al.*, *Strontium-90 on the Earth's Surface II*, TID-17090 (November 1962).

Table 6.6. Observed and Expected Specific Activities (Atoms ^{90}Sr/Atoms Sr) in Clams as a Function of the Dilution of Clinch River Water by Tennessee River Water

Collection Site and Distance from White Oak Creek	Dilution Factor for Clinch River Water	Specific Activity		Number Analyzed
		Expected on the Basis of Dilution	Observed by Stable Chemistry and Radiochemistry	
		$\times 10^{-11}$	$\times 10^{-11}$	
CRM 47,[a] 26 miles upstream (control point)			1.67 ± 0.50[b]	12
CRM 17–4.7, 4–17 miles downstream (index point)	1	(130.8)[c]	130.8 ± 22.7	12
TRM 521,[a] 68 miles downstream	5.6	23.4	25.74 ± 3.36	19
TRM 425, 163 miles downstream	7.05	18.6	19.78 ± 1.71	19
TRM 100, 489 miles downstream	12.3	10.6	10.14 ± 1.81	14

[a] CRM, Clinch River Mile; TRM, Tennessee River Mile; the Clinch River joins the Tennessee River at TRM 568.

[b] All averages ± 1 standard error.

[c] The specific activity in clams from the index point is the basis for specific activities expected because of dilution.

parently, ^{90}Sr concentrations in the Tennessee River up to 500 river miles from the release point may be predicted on the basis of dilution. These results, obtained in 1961, agree with those obtained in the water sampling and analysis programs of the Clinch River Study (Chap. 5).

CHIRONOMUS AS AN INDEX ORGANISM OF MUTAGENIC AGENTS

Waste releases from the Laboratory include a complex of chemicals as well as low levels of radioactivity. Aquatic organisms exposed to this mixture might suffer genetic insults from both the chemicals and the radiation, although effects of the latter were assumed to be of primary importance.[13] *Chironomus tentans,* commonly known as a midge, was selected as a species in which it might be possible to detect the effects of chronic releases of low-level radioactive wastes.[14]

Larvae of *C. tentans* live in the bottom sediments of the aquatic environment, where high concentrations of released radioactivity are sorbed. Since developmental stages of organisms are more sensitive to the effect of ionizing radiation than are mature individuals,[15,16] and because quantitative cytogenetic techniques may be used to describe the effects, Diptera larvae should be useful as indicators of the effects of ionizing radiation. *Chironomus tentans* has an added advantage because it is widely distributed in Europe and North America. This organism may be especially sensitive to radiation, since the germ cells are produced in larvae living in the mud.[17] Breaks occurring in the chromosomes are not repaired until fertilization; consequently, there is a greater probability for multiple breaks and formation of inversions.

Estimated Radiation Doses

Radiation dose to these bottom organisms was calculated by assuming that they received a submersion dose of beta radiation and a one-half submersion dose of the gamma radiation. These calculations also assumed that there were equal concentrations (by weight) of radionuclides in the organisms and in the mud. Furthermore, a reciprocity relationship was implied in which the absorbed dose derived from radionuclides within the organism was equal to the absorbed dose in the organism derived from radionuclides in the mud. *Chironomus tentans* larvae build mud tubes in the bottom sediment, and, since the radioactivity in the sediment was about four orders of

[13] D. J. Nelson and B. G. Blaylock, "The Preliminary Investigation of Salivary Gland Chromosomes of *Chironomus tentans* Fabr. from the Clinch River," pp. 367–72 in *Radioecology,* Reinhold, New York, 1963.

[14] B. G. Blaylock, S. I. Auerbach, and D. J. Nelson, *Chromosomal Aberrations in a Natural Population of* Chironomus tentans *Exposed to Chronic Low-level Environmental Radiation,* ORNL-3531 (Jan. 14, 1964).

[15] A. D. Welander, "Some Effects of X-Irradiation of Different Embryonic Stages of Trout (*Salmo gairdnerii*)," *Growth* 18(4), 227–55 (1954).

[16] L. B. Russell and W. L. Russell, "An Analysis of Changing Radiation Response of the Developing Mouse Embryo," *J. Cell. Comp. Physiol.* 43 (Suppl. 1), 103–49 (1954).

[17] S. E. Abul-Nasr, "Structure and Development of the Reproductive System of Some Species of Nematocera (Order Diptera: Suborder Nematocera)," *Phil. Trans. Roy. Soc. London, Ser. B* 234, 339–96 (1950).

magnitude greater than in the overlying water,[18] radioactivity in the water could be disregarded for the purpose of this calculation. The submersion dose calculation assumed that the organisms are in the center of an infinite sphere and receive equal quantities of radiation from all directions. The penetration distance of beta particles in a dense material such as mud is short with respect to the depth of *C. tentans*; therefore the complete submersion dose was calculated in this manner. For the more penetrating gamma radiation, the one-half submersion dose was used, because the organisms for the most part receive radiation only from one-half of a sphere.

Standard dose-rate equations were used to calculate dose rates of *C. tentans* from both natural background and the released radionuclides.[13] The natural background from external emitters, internal emitters, and cosmic radiation was estimated at 0.230 rad/year. Radiochemical analyses of bottom sediments[18] were used in calculating external dose rates contributed by the contaminated sediments. The bottom samples were collected at 11 transects from CRM 21.3 to 1.1, and the average radionuclide content at these transects was used to calculate dose rates. The concentration of radioisotopes from CRM 16.3 to 19.1 was approximately twice the average value of that for the entire river. Thus, over several miles of river, there were areas where doses were about twice as high as the average doses in the river from CRM 21.5 to 1.1. Radioassays of the sediments under the standing pool behind White Oak Dam[19] indicated radioisotope concentrations in the creek about 50 times higher than those in the river. Diptera populations were subject to the following doses of radiation:

Background	0.230 rad/year	
Average CRM 21.5 to 1.1	4.37 rads/year	19 times background
Average CRM 19.1 to 16.3	8.52 rads/year	37 times background
White Oak Creek	~230.0 rads/year	~1000 times background

The life cycle of *C. tentans* requires from 26 to 61 days.[20] This wide range of time to complete the life cycle is not unusual among insects with aquatic life stages. Most individuals of *C. tentans* complete their life cycles in about 30 days, of which 3 days are spent as an adult. Larvae are found in the bottom sediments throughout the winter; adults are observed from spring throughout fall and during warm periods in the winter.

Chromosomal Polymorphism

Fourth instar larvae collected from White Oak Creek and from other local populations living in uncontaminated areas were analyzed for chromosomal aberrations. Table 6.7 shows the results of these analyses. Seventeen different aberrations were found in the population living in the

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[18] J. C. Hart, *Appl. Health Phys. Ann. Rept. 1959*, ORNL-3073 (Mar. 20, 1961).

[19] E. G. Struxness, *Detailed Assessment of Solid and Liquid Waste Systems — Hazard Evaluations*, vol. 4, ORNL-CF-60-5-29 (May 31, 1960).

[20] W. O. Sadler, "Biology of the Midge *Chironomus tentans* Fabricius, and Methods for Its Propagation," Cornell Univ. Agr. Exp. Sta. Memoir No. 173 (1935).

Table 6.7. Chromosomal Aberrations in Irradiated and Nonirradiated Natural Populations of *Chironomus tentans*

	Irradiated Population	Nonirradiated Population
Number of larvae analyzed	692	714
Number of different aberrations found in each population	6	6
Number of different aberrations unique to one population	11	0
Total number of aberrations observed in each population	345	372
Average aberration per larva	0.50	0.52

contaminated area, while only six different aberrations were found in the population from uncontaminated areas. All six of the aberrations found in the unirradiated population were also found in the irradiated population and were considered endemic to the populations of this area. Three of these aberrations – paracentric inversions – were found at a relatively high frequency ranging from 9 to 22%. These three inversions accounted for the majority of the aberrations found in both the irradiated and nonirradiated population. The average aberration per individual in the irradiated area was 0.50 per larva and 0.52 per larva in the nonirradiated population. Eleven aberrations, including ten inversions and one deletion, were unique to the irradiated population. All these unique aberrations were found at a very low frequency, most of them only one time. This unusually large number of unique aberrations in a sample of this size led to the conclusion that new chromosomal aberrations were being introduced into the natural population of *C. tentans* living in the area contaminated by radioactive waste but were eliminated rapidly by natural selection.

Chromosomal polymorphism is known to occur in many organisms, and the high frequency of the three paracentric inversions indicates that they are well established in the natural populations of *Chironomus tentans* in this area. Inversions which have selective value become established in a natural population at some frequency. Usually these inversions are maintained in the population because the inversion heterozygote is better adapted than either homozygote. These inversions, which preserve the integrity of highly adaptive gene arrangements, help the species meet changing environmental conditions.

The frequency of the endemic inversions in the irradiated population was compared with that of the nonirradiated population. Since inversion frequencies may fluctuate with season, collections from the irradiated and nonirradiated population were made during the same week. Table 6.8 shows that there was no significant difference in the frequencies of these inversions. Thus the frequencies of these three inversions, which undoubtedly are maintained in the population by some selecting factors, were not affected by the increased levels of irradiation.

Table 6.8. Frequency of Inversion Heterozygotes in Irradiated and Nonirradiated Natural Populations of *Chironomus tentans*

	Irradiated Population White Oak Creek 1962–64	Nonirradiated Population Ten-Mile Creek 1962–64	X^2	P^a (1 d. f.)
Number of larvae analyzed	439	407		
Inversion 1Ra	67	74	1.29	0.50–0.25
Inversion 2Lab	99	90	0.02	0.90
Inversion 3Ra	36	37	0.22	0.75–0.50

[a]Probability with 1 degree of freedom.

Results of these radiation effects studies suggest that increased levels of radioactivity should increase the numbers of new mutations in a population. According to genetic theory, new mutations in organisms will either have an adaptive value and be maintained in the population, or will be eliminated by natural selection. Results of this study with *Chironomus tentans* show that new chromosomal aberrations were eliminated from the population without affecting the previously established chromosomal polymorphism.

BIOLOGICAL VECTORS AND RESERVOIRS

Organisms incorporating radionuclides in their tissues may affect the distribution of radioactivity in the river to a minor extent, and movements of the organisms may redistribute the incorporated isotope to other environments. The extent to which such translocations may take place is dependent upon the concentration of radionuclides and the quantity of biomass involved.

A maximum estimate of the radioactivity incorporated in the biota may be made with knowledge of the volume of water in the Clinch River embayment of Watts Bar Reservoir (10^9 ft^3) and its phosphate concentration (0.2 mg/liter). If it is assumed that all the phosphorus is incorporated in the biota, and the biota contain 0.5% phosphorus by weight, the maximum amount of biomass in the river (4×10^8 g) can be calculated. Then, considering the maximum concentration of ^{90}Sr observed in fish (75 picocuries/g), the total ^{90}Sr load in the biota would be 30 mc. A similar calculation for ^{137}Cs results in a maximum value of about 8 mc.

Tubificid Worms

Tubificid worms are the most abundant organism in the river bottom sediments. They burrow their heads in the bottom sediments, and their tails extend into the overlying water. They defecate into the water, and the fecal pellets fall back. There are density currents in the rivers, and these, coupled with the feeding activity of the worms, might contribute to the downstream movement of bottom sediments.

The effects of the worms could not be measured directly in the field; consequently, parameters regarding their feeding activities were measured in the laboratory, and a mathematical model was used to extrapolate to the environment.[21] On the basis of the feeding activity of 1 worm/cm^2, it was found that it would take 0.333 year to move the sediment 9.18 cm downstream. Worm populations in the river average 1 per 10 cm^2; hence the effect of these populations on the movement of contaminated sediment would be insignificant.

Clams

Earlier studies showed that freshwater clams concentrated strontium in their shells by factors of 2500 to 9000 times that in water and, therefore, might be useful as indicators of ^{90}Sr in the environment. Since there is a commercial clam fishery on the Tennessee River downstream from the confluence of the Clinch River, calculations were made to estimate the removal of ^{90}Sr from the river in clamshells. The annual harvest[22] of shells ranges from about 4.5×10^9 to 9×10^9 g. Considering the maximum harvest and the average ^{90}Sr concentration in clamshells (7.0×10^{-6} μc), the calculated removal of ^{90}Sr would be 63 mc/year. If ^{90}Sr releases were constant and if growth of the population was in equilibrium with the harvest, a similar amount of ^{90}Sr would be incorporated into the population each year. These mollusk populations were studied recently,[23] and from this investigation it is reasonable to estimate a total population of approximately 4.5×10^7 clams in this area. Assuming a weight of 250 g for each clam (actually a high value) and using the average ^{90}Sr concentration, the reservoir of ^{90}Sr in the clams in the river would be 79 mc. The reservoir of ^{90}Sr in clams is small when compared with Laboratory releases of ^{90}Sr, which, from 1949 until 1961, ranged from 22 to 150 curies/year (Table 3.5).

Aquatic Insects

Another possibility is translocation of radioactivity in the bodies of aquatic insects which live in the bottom sediments and fly to land upon maturity. To test the effect of this vector, a large collection of adult chironomids was caught in an insect light trap operated on the Clinch River bank. These adult chironomids contained $(3.55 \pm 1.13) \times 10^{-6}$ μc of ^{90}Sr per g, and 8.76 times as much ^{90}Sr activity as an equal quantity of bottom sediment from that location. Studies elsewhere[24–26] have shown emergent chironomid biomass ranges from several g m^{-2} year^{-1}

[21] R. J. Morton (ed.) *et al.*, *Status Report No. 1 on Clinch River Study*, Clinch River Study Steering Committee, ORNL-3119 (July 27, 1961).

[22] Tennessee Valley Authority, *Division of Forestry Development, Annual Report – 1964* (not dated).

[23] G. D. Scruggs, Jr., "Status of Freshwater Mussel Stocks in the Tennessee River," U.S. Fish and Wildlife Serv. Spec. Sci. Rept. Fisheries No. 370, December 1960.

[24] H. T. Odum, "Trophic Structure and Productivity of Silver Springs, Florida," *Ecol. Monographs* 27, 55–112 (1957).

[25] J. M. Teal, "Community Metabolism in a Temperate Cold Spring," *Ecol. Monographs* 27, 283–302 (1957).

[26] R. C. Dugdale (unpublished thesis), quoted from G. F. Lee, "Studies on the Iron Manganese, Sulfate and Silica Balances and Distributions for Lake Mendata, Wisconsin," *Wis. Acad. Sci.* 51, 141–55 (1962).

up to about 20 g m^{-2} $year^{-1}$, the higher productivities arising from eutrophic situations. The Clinch River is not greatly enriched with organic matter; therefore, productivity of 10 g m^{-2} $year^{-1}$ is a reasonable estimate. With this productivity, emergent chironomids would remove $(3.55 \pm 1.13) \times 10^{-5}$ μc of ^{90}Sr per m^2 per year from the river bottom. The average increment of ^{90}Sr from fallout in the United States[12] between 1959 and 1960 was 4.2×10^{-3} curie/mile^2 (1.62×10^{-3} $\mu c/m^2$). Thus, fallout entering the river directly would add about 45 times as much ^{90}Sr as might be removed by the emerging chironomids. Movement of insects from a contaminated terrestrial environment was found to play a similar, inconsequential role in the dispersal of radioactivity.[27] Thus, it appears that the dispersion of ^{90}Sr by insects would not be important.

The general observation that biota in an environment do not contain significant amounts of a chemical element is consistent with biogeochemical principles. Specific studies of the possible role of organisms as reservoirs and vectors of radioactivity movement show that biological activities per se are generally inconsequential in the dispersion of radioactivity. Localized problems may exist,[28] but general contamination of the landscape by mobile organisms is unlikely.

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[27] D. A. Crossley, Jr., "Movement and Accumulation of Radiostrontium and Radiocesium in Insects," in *Radioecology*, ed. by V. Schultz and A. W. Klement, Jr., Reinhold, New York, 1963.

[28] J. J. Davis, "Dispersion of Radioactive Materials by Streams," *J. Am. Water Works Assoc.* 50(11), 1501–15 (1958).

7. Safety Evaluation of Radioactivity in Clinch-Tennessee Rivers

ESTIMATED DOSES FROM INTAKE OF CONTAMINATED WATER

Estimates of fractions of maximum permissible doses received from drinking Clinch River and Tennessee River water were based on concentrations of radionuclides in the raw water. The mean annual concentration of radionuclides in the Clinch and Tennessee Rivers (Tables 7.1 and 7.2) was computed under the assumption that White Oak Creek water is completely mixed with river water.[1] It was further assumed that there would be no reduction of these radionuclide concentrations in water by water treatment before drinking.

[1]K. E. Cowser and W. S. Snyder, *Safety Analyses of Radionuclide Release to the Clinch River*, ORNL-3721, Suppl. No. 3 (May 1966).

Table 7.1. Calculated Mean Annual Concentration of Radionuclides in Clinch River Water at CRM 14.4

units of 10^{-9} μc/ml or pc/liter

Year	Gross Beta	^{137}Cs	^{106}Ru	^{90}Sr	^{91}Y	^{144}Ce	^{95}Zr	^{95}Nb	^{131}I	^{60}Co
1944	100			40						
1945	100			30						
1946	200			50						
1947	60			20						
1948	130			40						
1949	150	16	22	30	0	3.7	36	4.6	16	
1950	32	3.2	3.9	6.5	0		2.5	7.2	3.2	
1951	18	3.6	3.2	5.2	0		0.82	0.40	3.2	
1952	53	2.4	3.6	18	0	5.6	4.7	4.4	4.8	
1953	78	1.7	6.8	35	0	1.7	2.0	0.93	0.54	
1954	140	8.2	4.2	51	11	8.9	5.2	3.5	1.3	
1955	100	15	7.1	22	13	20	1.2	1.2	1.6	1.5
1956	130	38	6.5	23	7.6	13	2.6	3.4	0.78	10
1957	70	16	11	15	5.5	2.2	4.0	1.3	0.21	0.85
1958	110	11	8.4	30	18	6.0	1.2	1.2	1.7	1.8
1959	300	25	170	19	11	16	8.7	9.5	0.16	24
1960	550	7.7	480	6.9	5.1	6.7	9.3	11	1.3	18
1961	520	3.5	480	5.2	0.35	0.98	4.6	17	0.87	7.3
1962	270	1.0	260	1.8	0.30	0.23	0.40	1.4	0.067	2.6
1963	100	0.76	94	1.7	0.35	0.33	0.074	0.16	0.096	3.1

Table 7.2. Calculated Mean Annual Concentration of Radionuclides in Tennessee River Water at TRM 465.5

units of 10^{-9} $\mu c/ml$ or pc/liter

Year	Gross Beta	^{137}Cs	^{106}Ru	^{90}Sr	^{91}Y	^{144}Ce	^{95}Zr	^{95}Nb	^{131}I	^{60}Co
1944	20			5						
1945	20			4						
1946	20			6						
1947	8			2						
1948	16			4						
1949	18	2.0	2.7	3.7	0	0.46	4.5	0.57	2.0	
1950	4.9	0.49	0.60	0.98	0		0.38	0.11	0.49	
1951	3.1	0.61	0.54	0.87	0		0.14	0.068	0.54	
1952	8.1	0.37	0.56	2.7	0	0.86	0.72	0.68	0.74	
1953	12	0.26	1.1	5.4	0	0.27	0.30	0.14	0.083	
1954	17	0.94	0.48	5.8	1.2	1.0	0.59	0.40	0.15	
1955	16	2.3	1.1	3.4	2.0	3.1	0.19	0.21	0.26	0.24
1956	21	6.2	1.1	3.8	1.2	2.1	0.42	0.55	0.13	1.7
1957	9.8	2.2	1.5	2.1	0.78	0.31	0.56	0.18	0.030	0.12
1958	18	1.8	1.4	4.8	3.0	0.97	0.20	0.20	0.32	0.28
1959	36	2.9	20	2.3	1.3	1.9	1.1	1.1	0.02	2.8
1960	79	1.1	67	1.0	0.73	0.96	1.3	1.6	0.19	2.6
1961	67	0.47	61	0.67	0.05	0.13	0.59	2.1	0.11	0.93
1962	40	0.15	38	0.26	0.044	0.034	0.059	0.21	0.010	0.38
1963	17	0.12	15	0.28	0.056	0.053	0.012	0.025	0.015	0.49

The fractions of MPC_w attained were calculated according to the recommendations of ICRP.[2] For a mixture of invariant composition taken up by a particular organ, x, the fraction of MPC_w attained is given by

$$\sum_i \frac{P_{wi}}{MPC_{wi}^x} ,$$

where

P_{wi} = concentration of the particular radionuclide in water and

MPC_{wi}^x = maximum permissible concentration for continuous exposure of the critical organ to a particular radionuclide in water.

The values of P_{wi} are average values, averaged over a period of one year according to the recommendations of ICRP, NCRP, and FRC.[2–6] All MPC_w values applicable to the Clinch River

[2] *Report of Committee II on Permissible Dose for Internal Radiation*, International Commission on Radiological Protection, Publication 2, Pergamon, London, 1959.

[3] *Recommendations of the International Commission on Radiological Protection* (as amended 1959 and revised 1962), ICRP Publication 6, Pergamon, London, 1964.

[4] "Background Material for the Development of Radiation Protection Standards, Report No. 1," *Staff Report of the Federal Radiation Council* (May 18, 1960).

[5] "Background Material for the Development of Radiation Protection Standards, Report No. 2," *Staff Report of the Federal Radiation Council* (Sept. 26, 1961).

[6] "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure," *NBS Handbook No. 69*, 1–95.

situation were taken as 1/10 of the occupational MPC_w values for exposure during a 168-hr week. To obtain MPC_w values relating to the Tennessee River, the MPC_w for continuous occupational exposure (168 hr/week) was multiplied by 1/100 for whole body as the critical organ and by 1/30 for thyroid, bone, and GI tract as the critical organs.

Table 7.3 gives the fraction of MPC_w of the river water calculated on the basis of the average concentrations of the various radionuclides for each year. It can be seen that the estimated exposure to the bone was highest, attaining 0.13 of the MPC_w in the Clinch River in 1954. If these fractions are multiplied by the appropriate dose rate permitted in the particular organ, an estimate of the annual dose rate is obtained. However, careful interpretation of these dose rates is necessary, since the calculated dose only applies to a long-term, stable situation. MPC_w values are set with a requirement that the dose rate (rems/week) to adults after 50 years of exposure will not exceed a recommended limit. In the case of ^{90}Sr, with its long effective half-life, the allowable annual dose rate is reached only after 50 years of continuous exposure to the MPC_w. Because the MPC's which enter into the calculations are based on so-called "standard man," the dose represents only that which would be received by a person of physical characteristics and habits resembling standard man.

Mathematical models were devised to calculate the radionuclide burden and dose received by a critical organ due to the ingestion of known concentrations of radionuclides. Correction factors

Table 7.3. Fraction of MPC in Water from Clinch and Tennessee Rivers

Year	Clinch River Mile 14.4				Tennessee River Mile 465.5			
	Bone	GI Tract	Total Body	Thyroid	Bone	GI Tract	Total Body	Thyroid
1944	0.1		0.06	0.02	0.04		0.07	0.006
1945	0.08		0.04	0.01	0.03		0.06	0.005
1946	0.1		0.07	0.02	0.05		0.09	0.008
1947	0.05		0.03	0.01	0.02		0.03	0.003
1948	0.1		0.06	0.02	0.03		0.06	0.005
1949	0.076	0.0043	0.044	0.021	0.028	0.0016	0.054	0.0077
1950	0.016	0.0022	0.0094	0.0043	0.0073	0.0010	0.014	0.0021
1951	0.013	0.0017	0.0075	0.0038	0.0066	0.00087	0.013	0.0019
1952	0.044	0.0015	0.025	0.0098	0.020	0.00069	0.039	0.0045
1953	0.087	0.0018	0.050	0.015	0.040	0.00053	0.076	0.0053
1954	0.13	0.0032	0.072	0.022	0.044	0.0011	0.083	0.0074
1955	0.054	0.0037	0.032	0.0099	0.026	0.0019	0.050	0.0047
1956	0.059	0.0042	0.035	0.010	0.029	0.0020	0.057	0.0051
1957	0.037	0.0024	0.022	0.0063	0.016	0.00099	0.030	0.0027
1958	0.074	0.0031	0.043	0.013	0.034	0.0015	0.069	0.0077
1959	0.049	0.021	0.029	0.0084	0.018	0.0075	0.034	0.0030
1960	0.017	0.050	0.011	0.0037	0.0076	0.021	0.015	0.0016
1961	0.013	0.048	0.0077	0.0027	0.0050	0.019	0.0099	0.0010
1962	0.0044	0.026	0.0028	0.00083	0.0023	0.013	0.0040	0.00037
1963	0.0043	0.0096	0.0026	0.00093	0.0024	0.0052	0.0042	0.00038

were applied taking into account differences due to intake and organ size as a function of the individual's age. Figure 7.1 illustrates the magnitude of these differences in the skeleton as estimated on the basis of existing data.[7–10] The base line represents the ratio of intake to organ weight for standard man. The curves reflect the correction factors which account for changes in this ratio with age.

The dose received by the critical organ of an individual aged γ years during a particular exposure year, t, from intake during that year is given by[1,2,11]

$$D_t = \frac{\text{MPD}\ g_t\ h_\gamma}{1 - e^{-\lambda_e 50}} \left(1 - \frac{1 - e^{-\lambda_e}}{\lambda_e}\right),$$

where

MPD = maximum permissible dose rate to a particular organ, rems/year,

g_t = fraction of MPC_w in water during a particular year, t,

h_γ = dose correction factor for a particular age, γ, and

λ_e = effective elimination constant of radionuclide, 1/years.

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[7] Errett C. Albritton, *Standard Values in Nutrition and Metabolism*, Saunders, 1954.

[8] "Donnees Biologiques de Base pour l' etude des Niveauz de Contamination Applicables aux Enfants," Department de la Protection Sanitarie Contrat de' Association C.E.A. Euratom, February 1962, supplied to the ICRP by Dr. H. Jammet.

[9] William S. Spector (ed.), *Handbook of Biological Data*, Wright Air Development Center (October 1956).

[10] C. P. Straub, Robert A. Taft Sanitary Engineering Center, personal communication.

[11] H. Levin, "Some Aspects of Inhalation Dose Calculation from Single Exposures," *Health Phys.* 9, 41–44 (1963).

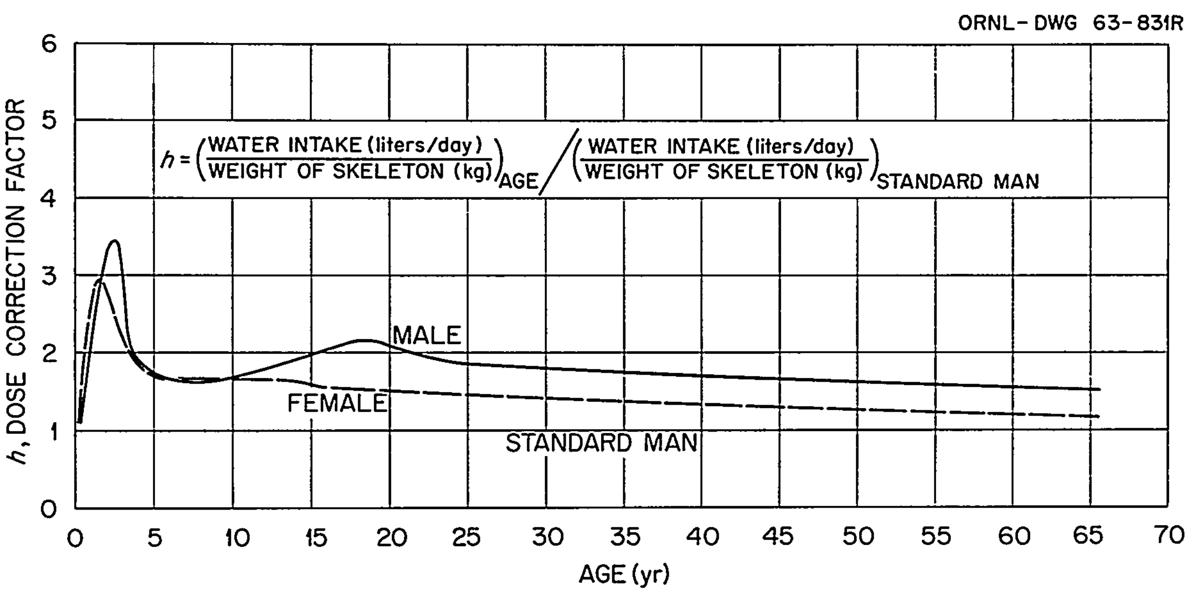

Fig. 7.1. Dose Correction Factor for Skeleton.

After the exposure period, t, the critical organ will continue to be irradiated by the radionuclides retained from the exposure period. The dose received during a subsequent year, τ, after the exposure period, t, is given by

$$D_{t,\tau} = \frac{\text{MPD}\ g_t\ h_\gamma\ (1 - e^{-\lambda_e})}{\lambda_e\ (1 - e^{-\lambda_e 50})}\ [e^{-\lambda_e(\tau - 1)} - e^{-\tau\lambda_e}] ,$$

where

τ = years after a particular intake period, t, and $1 \leqq \tau \leqq n$.

The mathematical models were coded for the Control Data 1604 digital computer. Calculations were performed by assuming that individuals of ages 0 (newborn infant) through 45 and standard man began to drink untreated water from the Clinch River (CRM 14.4) and from the Tennessee River (TRM 465.5) in 1944. They continued to drink water from these sources through 1963, after which their drinking water was obtained from an uncontaminated supply. All water taken into their bodies, in food or in other forms, was assumed to be equally contaminated.

The computed annual doses received by the skeleton, total body, and thyroid of males drinking Clinch River water are shown in Figs. 7.2, 7.3, and 7.4. At the end of 1963 the dose rate to the skeleton (Fig. 7.2) of the critical population group, the children 14 years old in 1944, was about twice that of standard man. Differences in doses are due to differences in intake and skeleton size. Strontium-90 is responsible for more than 99% of the skeleton dose. Smaller releases

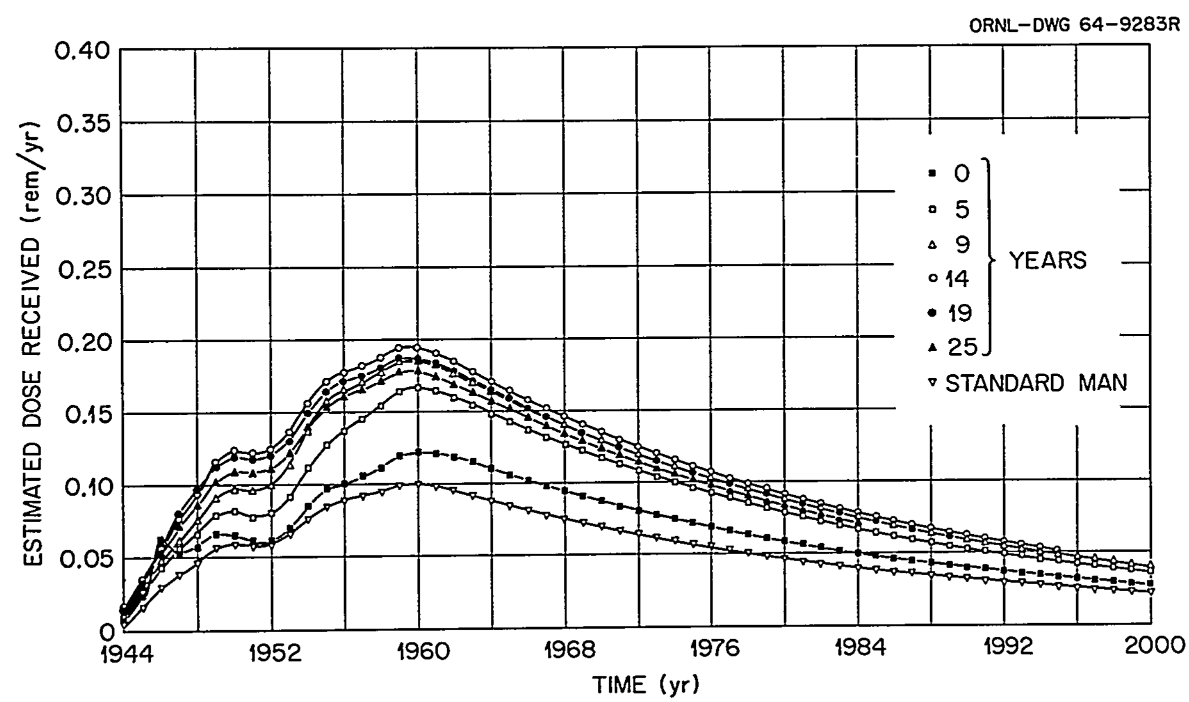

Fig. 7.2. Estimated Dose Received by Skeleton of Males from Drinking Clinch River Water.

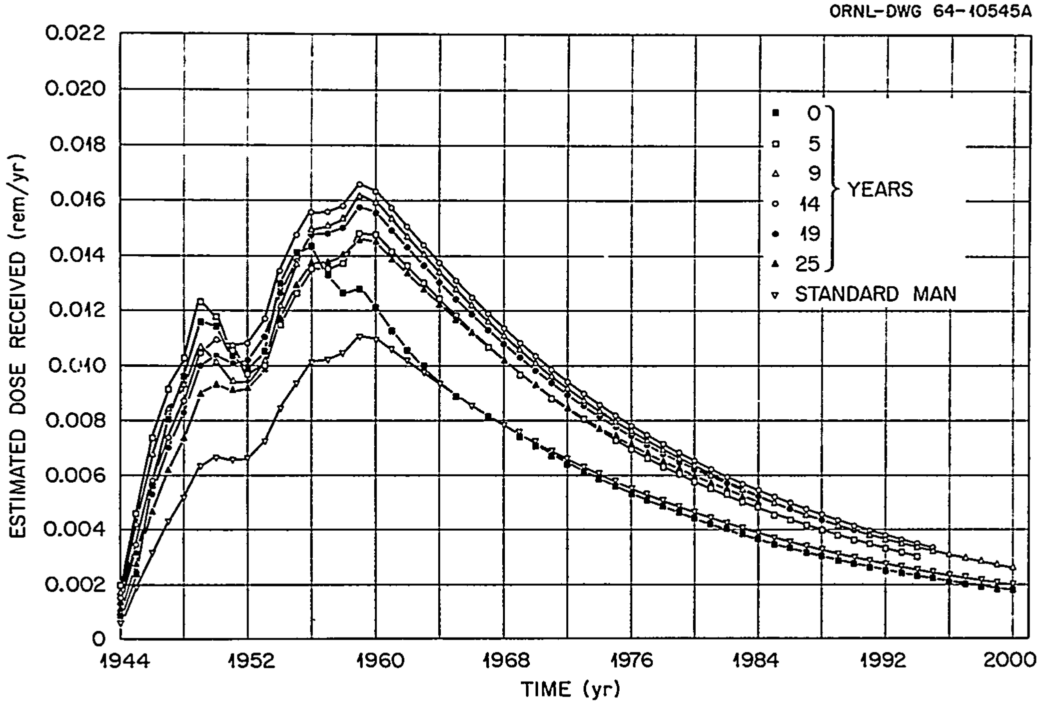

Fig. 7.3. Estimated Dose Received by Total Body of Males from Drinking Clinch River Water.

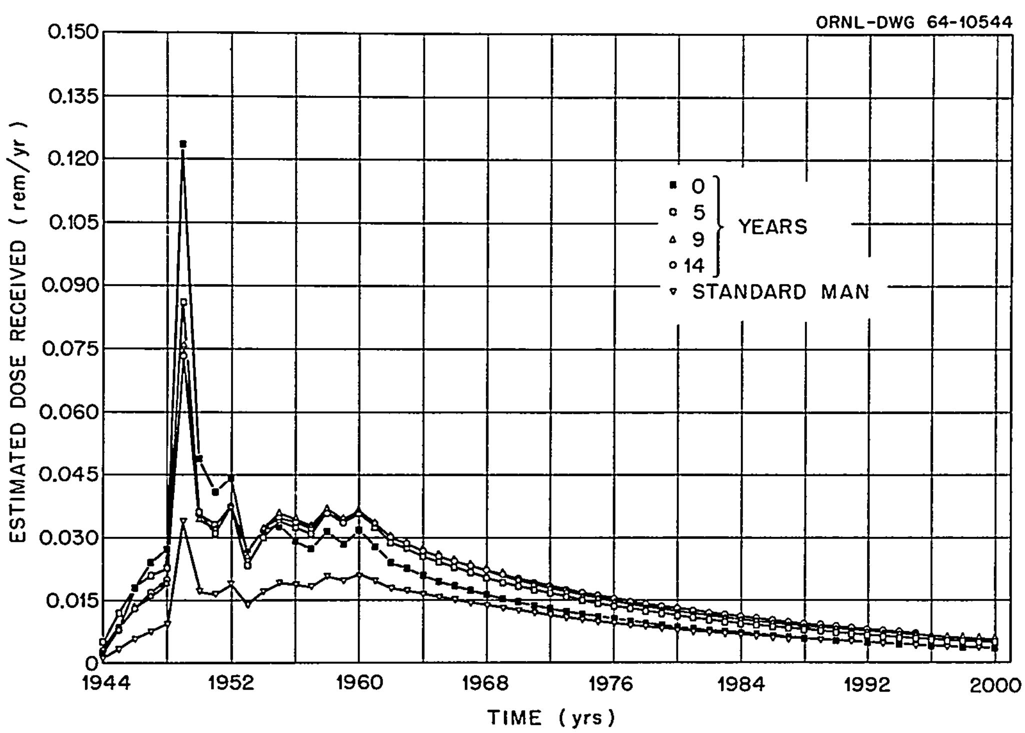

Fig. 7.4. Estimated Dose Received by Thyroid of Males from Drinking Clinch River Water.

of this radionuclide to the river in 1950 to 1952 are reflected in reduced doses during this interval. Note that dose rates to the skeletons of all age groups are considerably less than 1/10 of the continuous occupational levels recommended by ICRP (3.0 rems/year). Dose rates to the total body in 1963 (Fig. 7.3) and thyroid (Fig. 7.4) of the critical groups are about 50% higher than those of standard man, but well below acceptable limits. Similar differences are seen in the case of water intakes from the Tennessee River, but in all cases the dose rates to the critical organ of age groups on the Tennessee are at least one order of magnitude lower than permissible dose levels. For all age groups and critical organs considered, dose rates to the males are higher than those received by females.

Total Dose

Another interesting comparison is the estimated total dose to individuals during the period when Clinch River and Tennessee River water is assumed to have been used for drinking. As shown in Table 7.4 the skeleton of a 14-year-old male received a total dose of 2.9 rems from Clinch River water and 0.37 rem from Tennessee River water; this is about twice that received by standard man. The total body of the 14-year-old attained a 50% higher dose than standard man. About 99% of the total body dose was due to ^{90}Sr. The thyroid of the newborn infant received a dose about twice that of standard man. Strontium-90 and iodine-131 were responsible for 70 and 30% of the total thyroid dose respectively. A large release of ^{131}I resulted in a sizable increase in the estimated thyroid dose during 1949. Of all organs considered, the skeleton received the highest total dose. After 1963 the dose received is due to the radionuclides accumulated in the critical organs during the period of intake and can be considered a "dose commitment" for the future.

Table 7.4. Dose Received by Critical Organs of Males from Drinking Water[a] (rems)

Age at Start of Exposure	Clinch River Water			Tennessee River Water		
	Skeleton	Total Body	Thyroid	Skeleton	Total Body	Thyroid
0	1.7	0.20	0.65	0.23	0.026	0.087
5	2.3	0.22	0.61	0.30	0.029	0.082
9	2.6	0.23	0.60	0.34	0.029	0.079
14	2.9	0.23	0.59	0.37	0.030	0.078
19	2.8	0.22	0.53	0.36	0.028	0.070
25	2.6	0.20	0.48	0.34	0.026	0.063
Standard man	1.5	0.15	0.32	0.19	0.019	0.042
Maximum permissible dose[b]	60	10	60	20	1	20

[a]The cumulative dose for the period 1944 to 1963.

[b]According to recommendations of *ICRP Publication 2*, where values of annual dose rate for continuous occupational exposure are reduced to 1/10 and applied to the Clinch River and reduced to 1/30 for skeleton and thyroid as critical organ and to 1/100 for whole body as critical organ and applied to the Tennessee River.

ESTIMATED DOSES FROM INTAKE OF CONTAMINATED FISH

Fish that live in the Clinch River and Tennessee River downstream from White Oak Creek assimilate some of the radionuclides released to the river system. Since fish is a staple of man's diet, radionuclides present in the fish will contribute to the total radiation dose received by man.

An estimate was made of radionuclide intake from fish consumption by using the average concentrations of radionuclides in fish (Tables 6.3 and 6.4) and assuming an annual rate of fish consumption of 37 lb.[12] This rate of consumption applies to commercial fishermen, an admittedly high-exposure group. Dose calculations were made on the basis of an annual intake of 37 lb of bottom feeders, considering both the total fish (including bone) and the flesh, and of sight feeders, considering only the flesh. The fractions of the various bottom-feeder species caught were assumed to be distributed according to commercial harvests from Watts Bar Dam (see Table 6.5). Information on the sight feeders harvested and consumed was not available. Annual intakes were calculated by applying a fish dilution factor for East Tennessee fish (Table 6.5). This reduced the annual intakes by factors of about 2 to 4.

The fraction of MPI (maximum permissible intake) attained by the various critical organs was calculated (Tables 7.5 and 7.6) from the estimated intake of contaminated fish. Variation of the average percentages of MPI is indicated by the standard error of the mean. On the average, the percentage of MPI attained by consuming the total fish (bottom feeder) from the Clinch River during 1960–62 was 7.0 to 8.6%; the higher percentage resulted from including four carpsuckers (believed to have come from White Oak Creek) in the calculations. This range in percentage of the MPI was due to the concentration of ^{90}Sr in the bones of these fish, all of which were assumed to have been eaten. However, the consumption of 37 lb of total fish each year is rather unlikely. A recent survey of 80 fishermen by the Tennessee Fish and Game Commission did not indicate even an occasional ingestion of total fish. If only the flesh of bottom feeders was consumed, the percentage of MPI attained would be reduced to 1.5%. This value is about equal to the average intake received during 1960–62 from drinking untreated water. Further reduction in dose is likely due to dilution with other East Tennessee fish. In general, the flesh of sight feeders contributes about the same radionuclide burden to critical organs as the flesh of bottom feeders. An exception occurs in Tennessee River fish, for which there is no explanation at this time. The estimated percentage of MPI attained during 1963 was less than 1% for all the critical organs considered.

The dose received by the skeleton, total body, and thyroid due to consumption of contaminated water and fish was calculated by use of the models described earlier. In addition to the assumptions listed for the case of contaminated drinking water, it was assumed that 37 lb/year

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[12] P. Bryan and C. E. White, "An Economic Evaluation of the Commercial Fishing in the TVA Lakes of Alabama During 1956," *Proc. Twelfth Ann. Conf. Southeastern Assoc. Game and Fish Commissioners*, pp. 128–32, 1958.

Table 7.5. Estimated Percentage of MPI That Man May Attain by Consuming Clinch River Fish[a]

Fish Species	Sample Time	Critical Organ			
		Bone	Total Body	GI Tract	Thyroid
Bottom feeders[b] (flesh)	1960–62	1.5 ± 0.39	0.87 ± 0.23	0.072 ± 0.0081	0.38 ± 0.072
Bottom feeders[b] (flesh)	1963	0.27 ± 0.059	0.19 ± 0.034	0.030 ± 0.0035	0.060 ± 0.010
Bottom feeders[b] (total[c])	1960–62	7.0 ± 1.1 (8.6)[d]	4.1 ± 0.66 (5.0)	0.14 ± 0.014 (0.15)	1.4 ± 0.19 (1.6)
Bottom feeders[e] (flesh)	1960–62	0.60 ± 0.19	0.36 ± 0.11	0.03 ± 0.0039	0.16 ± 0.034
Bottom feeders[e] (flesh)	1963	0.11 ± 0.028	0.081 ± 0.016	0.013 ± 0.0018	0.024 ± 0.0049
Bottom feeders[e] (total)	1960–62	2.4 ± 0.28 (2.9)	1.4 ± 0.19 (1.7)	0.053 ± 0.0047 (0.0058)	0.48 ± 0.051 (0.57)
Sight feeders[f] (flesh)	1960–62	0.94 ± 0.43	0.61 ± 0.25	0.071 ± 0.012	0.31 ± 0.080

[a]The ratio of the estimated annual intake of radionuclides from consuming the particular category of fish to the maximum permissible intake (MPI) for the critical organ of interest. Thus these calculated percentages of MPI are not additive.

[b]Bottom feeders include carp, carpsucker, and buffalo.

[c]Total fish consists of flesh and bone.

[d]Parenthetical values include four carpsuckers (composited) collected at CRM 19.6.

[e]Intake adjusted by fish dilution factor.

[f]Sight feeders include white crappie, bluegill, white bass, largemouth bass, sauger, drum, and catfish.

Table 7.6. Estimated Percentage of MPI That Man May Attain by Consuming Flesh of Tennessee River Fish[a]

Fish Species	Sample Period	Critical Organ			
		Bone	Total Body	GI Tract	Thyroid
Bottom feeders[b]	1960–62	1.8 ± 0.36	3.7 ± 0.68	0.11 ± 0.014	0.55 ± 0.084
Bottom feeders[c]	1963	0.14 ± 0.039	0.33 ± 0.075	0.012 ± 0.0020	0.029 ± 0.0066
Bottom feeders[d]	1960–62	0.37 ± 0.071	0.69 ± 0.14	0.021 ± 0.0026	0.11 ± 0.017
Bottom feeders[d]	1963	0.066 ± 0.019	0.15 ± 0.037	0.0057 ± 0.00082	0.013 ± 0.0035
Sight feeders[e]	1960–62	4.0	7.6	0.11	0.83

[a]The ratio of the estimated annual intake of radionuclides from consuming the particular category of fish to the maximum permissible intake (MPI) for the critical organ of interest. Thus these calculated percentages of MPI are not additive.

[b]Bottom feeders include carp and carpsucker.

[c]Bottom feeders including carp and buffalo.

[d]Intake adjusted by fish dilution factor.

[e]Sight feeders include white crappie, bluegill, white bass, largemouth bass, sauger, drum, and catfish.

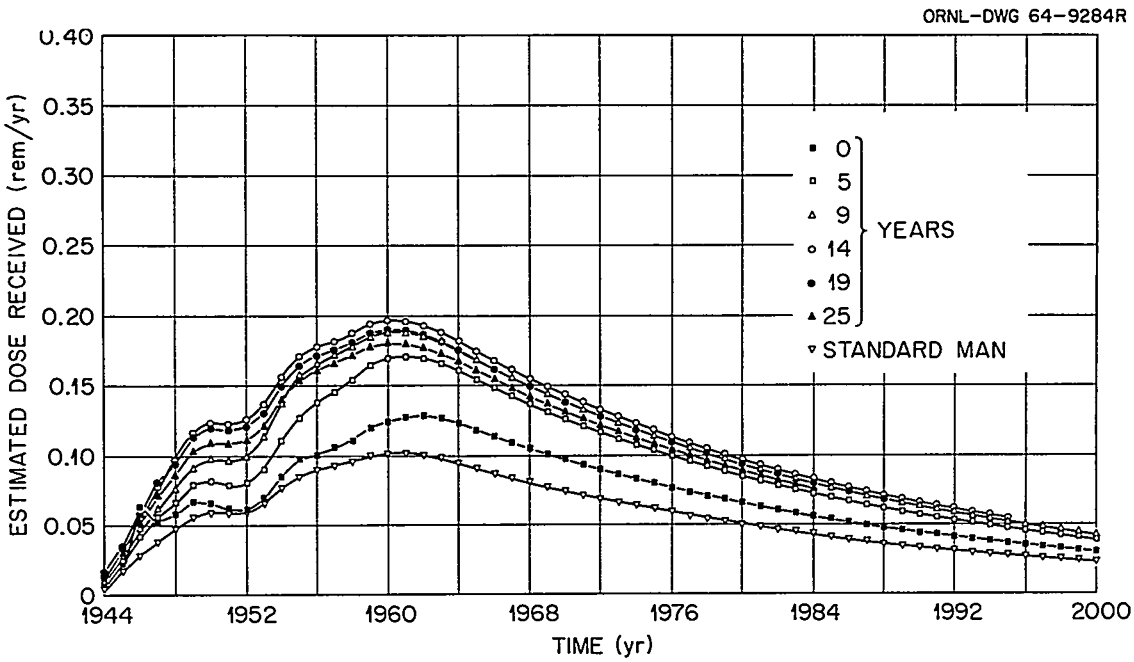

Fig. 7.5. Estimated Dose Received by Skeleton of Males from Drinking Clinch River Water and Consuming Contaminated Fish.

of the flesh of bottom feeders was consumed by standard man during the period 1960 to 1963. It was further assumed that the intake of fish was distributed as the intake of water; that is, the ratio of fish eaten by an individual to that of standard man is equal to the ratio of water consumed by the individual to that of standard man.

Figure 7.5 shows the computed annual dose to the skeleton due to the consumption of contaminated water and fish. By comparison with Fig. 7.2 it is seen that the net increase in dose rate to the skeleton is small. This is due to the fact that data for only four years of fish collection (1960–63) were available for the calculations, to the long effective half-life of ^{90}Sr, and to the reduction in ^{90}Sr releases to the river during this interval. The total dose received by all organs through 1963 is given in Table 7.7. The cumulative dose over the four-year exposure period is not excessive; the highest dose, about 300 millirems, was to the skeleton. Consumption of total fish could result in an increased dose by a factor of 5 to 10.

DOSE COMMITMENT ASSOCIATED WITH INGESTED RADIONUCLIDES

Another interpretation can be made of the internal dose calculations presented in the sections above. As a result of the intake of radionuclides with long effective half-lives, and in particular ^{90}Sr, the dose to the critical organ will continue for many years after intake. This constitutes a dose commitment for the future, rather than just a dose actually received during the period of intake. Doses will be delivered for various periods following intake depending on the

Table 7.7. Dose Commitment to Critical Organs of Males from Drinking Water[a] (rems)

Age at Start of Exposure — 1944	Clinch River Water			Tennessee River Water		
	Skeleton	Total Body	Thyroid	Skeleton	Total Body	Thyroid
0	0.033	0.0035	0.011	0.013	0.0014	0.0037
5	0.031	0.0032	0.0089	0.012	0.0012	0.0031
9	0.028	0.0029	0.0078	0.011	0.0011	0.0027
14	0.030	0.0026	0.0072	0.011	0.0011	0.0025
19	0.027	0.0026	0.0069	0.011	0.0010	0.0024
25	0.026	0.0025	0.0066	0.010	0.0010	0.0023
Standard man	0.015	0.0021	0.0047	0.006	0.0008	0.0016

[a]The cumulative dose for the period 1960–63.

effective half-life of radionuclides involved. For example, if the radionuclide in question is ^{131}I, then the dose due to ^{131}I intake will be received essentially in the following three to four weeks; but if the isotope in question is ^{90}Sr, the dose will be distributed throughout the remaining years of the individual's life.

The dose commitments associated with the consumption of Clinch and Tennessee River water are given in Table 7.11. These are the cumulative doses that individuals of various ages might receive, beginning in 1964 and extending to age 65 for each individual; they result from retention of the radionuclides ingested during the period 1944 through 1963. The critical organs of standard man generally have lower dose commitments than the organs of other age groups.

ESTIMATED DOSES FROM EXPOSURE TO CONTAMINATED WATER AND BOTTOM SEDIMENTS

The river system may serve as a source of external radiation to persons engaged in swimming, boating, fishing, and water skiing. Immersion dose rates were estimated by assuming that the exposed body is in the center of a sphere, receiving equal quantities of radiation from all directions. The external exposure from beta radiation in rads per day is given by[13]

$$\text{beta dose rate} = 51.2QE_i ,$$

where

Q = microcuries per gram of water,

$$E_i = 0.33E_m f\left(1 - \frac{\sqrt{Z}}{50}\right)\left(1 + \frac{\sqrt{E_m}}{4}\right),$$

E_m = maximum energy of type considered,

f = fraction of disintegration at a particular energy, and

Z = atomic number.

[13]K. Z. Morgan, "Physical Methods of Protection," Health Control and Nuclear Research (unpublished).

Similarly, the external exposure from gamma radiation in rads per day is given by

$$\text{gamma dose rate} = 51.2 Q E_m f .$$

The penetration distance in water of the most energetic beta particles involved is about 1 cm. Therefore, the beta radiation at the surface of a body immersed in contaminated water would be effectively one-half the calculated value.

The dose rate delivered by each radionuclide was calculated and then summed for the mixture of radionuclides to give the total dose rate. The total dose rate at CRM 14.4 and TRM 465.5 is shown in Fig. 7.6. A maximum dose rate of 0.027 millirad/day occurred at CRM 14.4 (1960). Until 1958 the largest fraction of beta dose was associated with ^{90}Sr and the largest gamma dose was due to ^{137}Cs. Since then, ^{106}Ru has accounted for about 75% of the total immersion dose.

Radionuclides associated with solids that have settled to the bottom of the river could contribute to the total dose. Bottom sediment dose rates were estimated from measurements

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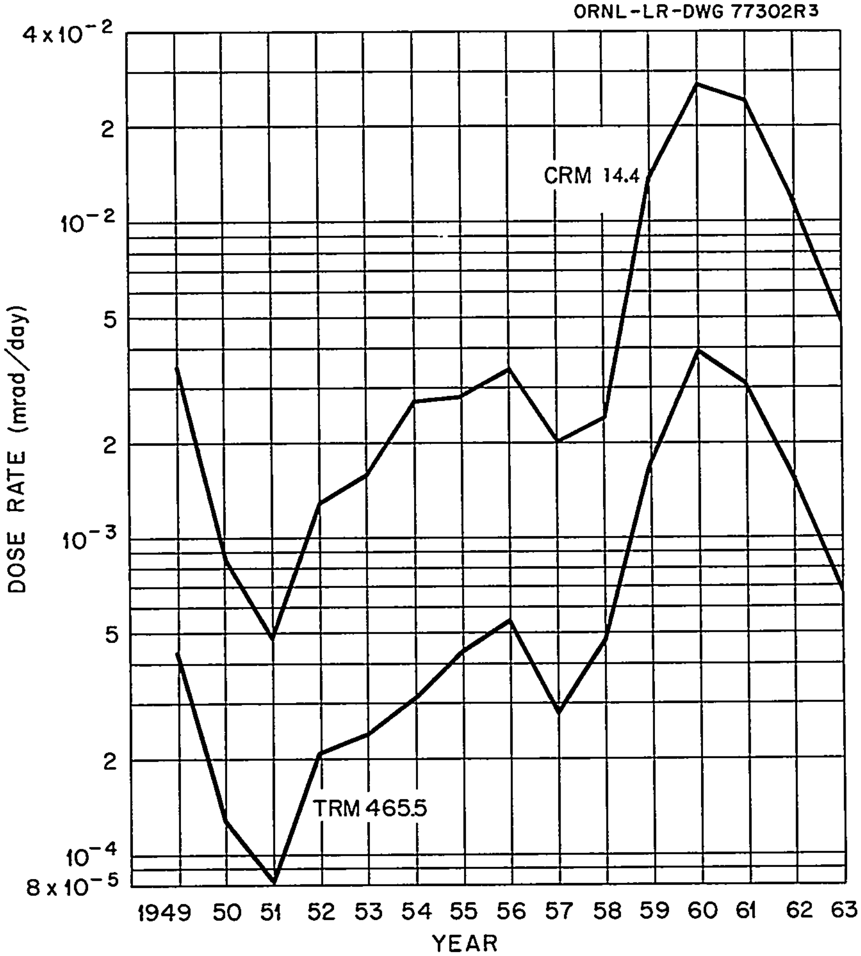

Fig. 7.6. Total Immersion Dose Rate at CRM 14.4 and TRM 465.5.

made with a gamma-sensitive detector known as the "Flounder." These measurements were converted to estimates of exposure dose rate by use of radium source calibration.[14] It was assumed that the average radionuclide composition of bottom sediments was uniformly distributed in an infinite source and that individuals would be exposed to one-half the dose due to beta particles. Also, only one-half the calculated gamma dose was considered, since the exposure is likely to result from 2π geometry.

Results of the estimation of bottom sediment dose rate for the Clinch and Tennessee Rivers are listed in Tables 7.8 and 7.9 respectively. Because the source is not infinite, the estimated values of gamma dose rate are higher than the "Flounder" measurements. Accordingly, the highest bottom sediment dose rate of 12 millirads/day for the Clinch River was in 1959, consisting of 40% beta and 60% gamma. Use was made of the relationship between "Flounder" measurements and estimated gamma dose rates (correlation coefficient of 0.90) to calculate the gamma dose rates in the Clinch River during 1950 to 1952. The total rare earths, ^{137}Cs, and, more recently, ^{106}Ru were the principal contributors to the beta dose rates, and ^{60}Co and ^{137}Cs accounted for the largest fraction of the gamma dose rate. Since bottom sediments are generally covered by water, some attenuation of the gamma flux would be expected. Three feet of water

[14] W. D. Cottrell, *Radioactivity in Silt of the Clinch and Tennessee Rivers*, ORNL-2847 (Nov. 18, 1959).

Table 7.8. Estimated Radiation Dose Rates from Contaminated Sediments in Clinch River

Measured[a] (millirads per 24-hr exposure)			Calculated (millirads per 24-hr exposure)			
Year	Average	Maximum	Beta	½ Gamma[b]	Total	Attenuated[c] ½ Gamma[b]
	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$
1951	39			90[d]		
1952	88			320[d]		
1953	53			160[d]		
1954	57	110	60	160	220	9.5
1955	60	110	130	180	310	11
1956	130	260	300	630	930	35
1957	96	180	180	460	640	24
1958	100	200	210	360	570	19
1959	160	280	450	710	1160	39
1960	150	280	510	460	970	25
1961	95	170	530	290	820	15

[a] In units of 10^{-2} millirad per 24-hr exposure as measured by the "Flounder."
[b] One-half of total gamma dose from infinite source.
[c] Attenuation through 3 ft of water.
[d] Estimated from correlation relationship.

Table 7.9. Estimated Radiation Dose Rate from Contaminated Sediments in Tennessee River

Measured[a] (millirads per 24-hr exposure)			Calculated (millirads per 24-hr exposure)			
Year	Average	Maximum	Beta	½ Gamma[b]	Total	Attenuated[c] ½ Gamma[b]
	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$
1951	13					
1952	22					
1953	23					
1954	19	30	22	50	72	3.0
1955	26	43	60	68	128	4.2
1956	36	69	65	110	175	6.1
1957	33	58	37	80	117	4.2
1958	35	63	55	62	117	3.5
1959	30	63	48	56	104	3.1
1960	33	49	75	61	136	3.3
1961	26	48	95	54	149	2.8

[a]In units of 10^{-2} millirad per 24-hr exposure as measured by the "Flounder."

[b]One-half of total gamma dose from infinite source.

[c]Attenuation through 3 ft of water.

shielding reduced the estimated gamma dose rate by a factor of about 20. These calculations indicated that the maximum exposure to contaminated water and sediments would be about 50 millirads in 100 hr of exposure.

ESTIMATED DOSES FROM EXPOSURE IN WATER TREATMENT PLANTS

The presence of radionuclides in the raw water entering a water treatment plant may create, through processes of concentration, an external or internal dose problem. Three water systems using Clinch River water as a source of supply were investigated. The Oak Ridge water plant has its raw water intake at CRM 41.5, well above the confluence of White Oak Creek and the Clinch River. The other two water treatment plants – the sanitary water plant serving the Oak Ridge Gaseous Diffusion Plant (ORGDP) and that serving the Kingston Steam Plant – have water intakes at CRM 14.4 and on the Emory River near CRM 4.4 respectively. The treatment plants are basically similar, differing only in design details.

The investigations consisted of external radiation surveys and collection of samples of sludge from various parts of the treatment plants and distribution systems. At the time of the surveys, various amounts of water had been treated since the last time settling basins had been cleaned or filters backwashed. Thus, there was a variation in the amount of sludge accumulated in the settling basins or sediment accumulated on the filters. Results of the external radiation survey (Table 7.10) showed little difference in dose rates in these plants using Clinch River

Table 7.10. Measurements of Ionizing Radiation in Water Treatment Plants[a] (millirads/hr)

System	Ground Surface	Flocculator	Settling Basin	6 in. Above Water in Settling Basin	Filter
Oak Ridge water plant	0.016	0.013	0.012	0.0097	0.0095
ORGDP	0.017	0.011	0.012	0.0092	0.0092
Kingston Steam Plant	0.015	0.0083	0.0087		0.015

[a]All measurements (except as noted) were made 3 ft above the walking surface of the particular component of the treatment plant.

water from points above and below the confluence of White Oak Creek. There was no significant difference between dose rates inside and outside the treatment plants, and values outside the plant were similar to those for the general Oak Ridge environment. Radionuclides may be sorbed to some extent by the anthracite filter media in the Kingston Steam Plant supply; however, the dose rate above the filters (0.015 mr/hr) was also influenced by the natural radioactivity present in the shale component of the block used for construction of the building.

CUMULATIVE DOSE TO EXPOSED POPULATIONS

The cumulative exposure of individuals or population groups that results from release of radioactive waste water to the Clinch River cannot be estimated precisely. One of the main reasons for this is the lack of information on habits and characteristics of the potentially exposed groups. Data on the location and age distribution of potentially exposed populations, the amounts of important foodstuffs consumed, the methods of food preparation, and the principal recreational habits are needed to estimate the cumulative dose. Differences in metabolic rates or processes of children or adults, in radionuclide removal from river water by suspended solids and by water treatment processes, and in the transfer of radionuclides from contaminated water to fish must also be considered. Although a critical population group may be defined for a particular exposure pathway, there is no reason to expect that the same critical population group will hold for all exposure pathways.

An estimate was made of the cumulative dose to the skeleton and total body of males working and residing in the Clinch River–Tennessee River environment (Table 7.11). Since the Clinch River below Oak Ridge does not serve as a source of municipal water (and children therefore would not consume this water), it was assumed that the youngest age group at the beginning of exposure (1944) would be the 18-year-old employed at ORGDP. It was further assumed that only one-half of the daily fluid intake would take place on the job, the other half being that due to the consumption of uncontaminated water off the job. The Tennessee River is used as a municipal water supply; consequently, the 14-year-old was assumed to be the critical population group. Dose calculations for exposures from recreational use of the environment (Table 7.11) were based on the following assumptions: (1) an exposure time of 100 hr per

Table 7.11. Estimated Cumulative Dose Received by Critical Organs of Males from Use of Clinch River and Tennessee River[a] (rems)

Critical Pathway	Clinch River		Tennessee River	
	Skeleton	Total Body	Skeleton	Total Body
Drinking water	1.4	0.11	0.38	0.030
Recreation	0.018	0.019	0.003	0.003
Fish	1.8	0.14	0.070	0.0057
Total	3.2	0.27	0.45	0.039
Maximum permissible dose[b]	60	10	20	1.0

[a]Aggregate exposure for the period 1944 to 1963.

[b]As recommended by ICRP (see refs. 4 and 8), the annual dose rates for continuous occupational exposure are reduced to 1/10 and applied to the Clinch River and are reduced to 1/30 for bone as critical organ and to 1/100 for total body as critical organ and applied to the Tennessee River.

year; (2) an attenuation of bottom sediment radiation by 3 ft of water; (3) the use of average concentrations of radionuclides found in water and sediments to estimate dose for periods where data were lacking; and (4) the adsorption of beta particles by the skin, thus limiting the exposure of the skeleton to gamma radiation only. Only the feet of the swimmer would be subjected to the total radiation from contaminated bottom sediments, and this would not be expected to exceed about 30 times the dose given in Table 7.11 for recreational use of the river. Occupational exposure from work within a water treatment plant would not be significantly different from background radiation and therefore not considered.

The cumulative dose due to consumption of contaminated fish was difficult to estimate. As shown in the section above on "Estimated Dose from Intake of Contaminated Fish," the fraction of MPI attained by standard man from consuming 37 lb/year of the flesh of contaminated bottom feeders was about equal to that from drinking contaminated water. However, the average fish consumption in the South is only 24 lb/year.[15] As a first approximation, it was assumed that the total dose from eating Clinch River fish was 24/37 of the dose due to drinking Clinch River water, 1.8 and 0.14 rems to the skeleton and total body respectively. It was further assumed that bottom feeders taken from the Tennessee River would be diluted with other East Tennessee fish, resulting in total doses of 0.07 rem to the skeleton and 0.0057 rem to the total body. The estimated cumulative dose to the skeleton of the 18-year-old utilizing the Clinch River was highest, 3.2 rems. Estimated total dose to the skeleton of the 14-year-old residing along the Tennessee River was 0.45 rem. In both cases the dose was less than one-tenth of the maximum permissible dose. These estimated doses are believed to be high because of the conservative assumptions made in their estimation.

[15]*Dietary Evaluation of Food Uses in Households in the United States*, U.S. Department of Agriculture, Household Food Consumption Survey 1955, Report 16, November 1961.

CROP IRRIGATION AS A POTENTIAL SOURCE OF RADIATION EXPOSURE

Agricultural irrigation increased significantly in Tennessee during 1950 to 1955. A survey conducted by the Tennessee Division of Water Resources indicated that in 1958, 1021 irrigation units were in operation; 20% were used for irrigating truck crops and 30% were used for feed crops.[16] Currently, crop irrigation along the Clinch River is nonexistent.[17] Therefore, an analysis of the consequences of possible transfer of fission products from contaminated river water to foods by irrigation is a hypothetical exercise. However, safety analyses are supposed to point out future problem areas as well as to assess the safety of current practices.

Since direct measurements of soil or crop loading with fission products due to irrigation were not available, it was necessary to calculate the exposure dose that man might receive on the basis of assumptions as to soil loading, fission product transfer coefficients from soil to crop, foliar contamination, and dietary habits. It was assumed that 2 ft/year of river water was uniformly applied by spray techniques over the irrigation area. The concentration of ^{90}Sr and ^{137}Cs in river water was chosen to be constant at the lowest levels present prior to 1961, that is, for ^{90}Sr the average concentration in 1951 and for ^{137}Cs the average concentration in 1953.

As irrigation water seeps into the soil, the stable ions and radioactive ions may be exchanged between soil and solution by ion exchange. The maximum fission product loading of the soil was estimated by assuming that the soil would continue to remove all applied exchangeable cations until saturated to the equilibrium value. The volume of irrigation water required to attain this equilibrium value was calculated from the distribution coefficients[18] for ^{90}Sr and ^{137}Cs and the mass of soil available. Distribution coefficients selected for this study were based on both calculated and measured values, 120 and 21,000 ml/g for ^{90}Sr and ^{137}Cs respectively. The mass of soil per square meter was taken as 2.24×10^5 g (from a soil depth of $6\frac{2}{3}$ in. and soil density of 1.32 g/cm^3). The depth of irrigation water required to attain equilibrium was calculated as 88 ft for ^{90}Sr and 16,000 ft for ^{137}Cs. The accumulation of fission products on the soil was calculated from the expression

$$N(t) = \frac{R}{\lambda + \alpha}\left[1 - e^{-(\lambda + \alpha)t}\right],$$

where

$N(t)$ = quantity of radionuclide present in the soil, μc/m^2,

R = rate of fission product application, μc year^{-1} m^{-2},

λ = decay constant of the fission product, year^{-1}, and

α = fractional loss per year of fission product to the crop, year^{-1}.

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[16] C. K. McLemore, "Irrigation in Tennessee — 1958," *Water Resources Division Paper, Department of Conservation and Commerce*, State of Tennessee.

[17] Kenneth Sutton, Roane County Agricultural Agent, personal communication.

[18] Distribution coefficient — the ratio of the concentration of radionuclide sorbed per unit weight of exchanger to the concentration of unsorbed radionuclide per unit volume of solution at equilibrium.

Although erosion, leaching, surface runoff, and interflow may remove some of the ^{90}Sr and ^{137}Cs from the soil, their effect on a well-managed agricultural system in East Tennessee was not known and consequently was assumed to be negligible. With suitable values chosen for α, the largest soil loadings at equilibrium for ^{90}Sr and ^{137}Cs were 0.071 and 0.014 $\mu c/m^2$ respectively. The external dose rate associated with these loadings is about 0.1 millirad per day of exposure.

Fission products may enter plants from the contaminated soil (soil-to-crop contamination) or by direct contamination of their above-ground tissues (foliar contamination). Plant growth requires that ions from the soil be removed continuously and relocated within the plant. This dynamic system allows fission products in soil to be transferred to the plant. Values reported for ^{90}Sr and ^{137}Cs transfer from soil to crop vary by a factor of about 10.[19–24] Many of the transfer coefficients are from experimental studies and require extrapolation to field conditions. Selection of transfer coefficients for this study considered the exchangeable calcium, cation exchange capacity, pH, and the exchangeable hydrogen of local soils. An estimated plant load ($\mu c/kg$, dry weight) is based on soil-to-crop transfers of 0.01% of the ^{137}Cs (all crops), 0.005% of the ^{90}Sr to wheat grain, and 1% of the ^{90}Sr to other crops. The quantity of radionuclide accumulated in edible parts of a plant due to foliar contamination depends on the stage of growth of the plant at the time of spraying and the rate of translocation and rate of accumulation of the radionuclide.[25] Intermittent rainfall is known to remove a fraction of the radionuclide deposited on plants. The assumed foliar retention of contaminants as a percent of that deposited per unit area was 1% of the ^{90}Sr and 5% of the ^{137}Cs by edible grains, 5% of the ^{90}Sr and 10% of the ^{137}Cs by edible leafy crops, and 0.03% of the ^{90}Sr and 10% of the ^{137}Cs by potatoes.[26–28] An edible crop yield of 1 kg/m^2 of irrigated soil was used for all crops except grain. The productivity of grain was assumed to be 20 bushels/acre or 0.14 kg/m^2. Contaminated milk was also considered to add fission prod-

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[19] *Report of the United Nations Scientific Committee on the Effects of Atomic Radiation*, United Nations General Assembly, Official Records: Seventeenth Session, Suppl. 16(A/5216), pp. 290 and 306, New York, 1962.

[20] R. G. Menzel, "Factors Influencing the Biological Availability of Radionuclides for Plants," *Federation Proc.* 22(6), 1398–1401 (Nov., Dec. 1963).

[21] E. M. Ramney *et al.*, "Plant Uptake of ^{90}Sr, ^{91}Y, ^{106}Ru, ^{137}Cs, and ^{144}Ce from Soils," *Soil Sci.* 83(5), 369–76 (May 1957).

[22] G. M. Milbourn, "The Uptake of Radioactive Strontium by Crops Under Field Conditions in the United Kingdom," *J. Agr. Sci.* 55(2), 273–82 (1960).

[23] G. M. Milbourn, F. B. Ellis, and R. Scott Russell, "The Absorption of Radioactive Strontium by Plants Under Field Conditions in the United Kingdom," *J. Nucl. Energy: Pt. A* 10, 116–32 (1959).

[24] D. A. Crossley, Jr., and H. F. Howden, "Insect-Vegetation Relationships in an Area Contaminated by Radioactive Wastes," *Ecology* 42(2), 302–17 (April 1961).

[25] L. J. Middleton, "Radioisotope in Plants: Practical Aspects of Aerial Contamination with ^{89}Sr and ^{139}Cs," *Radioisotopes in the Biosphere*, University of Minnesota Printing Department, 1960.

[26] R. G. Menzel, D. L. Myhre, and H. Roberts, Jr., "The Foliar Retention of Strontium-90 by Wheat," *Science* 134(3478), 559–60 (August 1961).

[27] *The Behavior of Radioactive Fallout in Soils and Plant*, Natl. Acad. Sci. – Natl. Res. Council, Publ. 1092, Washington, D.C., 1963.

[28] L. J. Middleton, "Radioactive Strontium and Cesium in the Edible Parts of Crop Plants After Foliar Contamination," *Intern. J. Radiation Biol.* 1(4), 387–402 (October 1959).

ucts to man's diet. In this case it was assumed that each liter of cow's milk contains 0.08% of the daily intake of ^{90}Sr and 1.3% of the daily intake of ^{137}Cs.[29]

The daily intake of ^{90}Sr and ^{137}Cs was estimated by assuming that all produce for the year comes from the same irrigated soil and that the dietary habits of the individual include an average daily intake of 0.24 kg of grain, 0.26 kg of leafy vegetables, and 0.1 kg of potatoes.[30] Most of the wheat grain is in the form of whole flour; therefore, only 25% of the ^{90}Sr in grain was expected to reach the flour and be consumed by man.[31] An MPI (μc/day) was calculated by taking a daily intake of 2.2 liters of water containing the maximum permissible concentration of the radionuclide of interest.

The contributions by all vectors to the MPI (bone) of ^{90}Sr are shown in Fig. 7.7. Similarly, the cumulative contributions to the MPI (total body) of ^{137}Cs are shown in Fig. 7.8. These calculations indicate that soil-to-crop transfer of ^{90}Sr may be of greatest long-term importance in contributing ^{90}Sr to man's diet from contaminated irrigation water. The intake of ^{90}Sr at equilibrium may result in 0.19 MPI for Clinch River water and 0.10 MPI for Tennessee River water. Foliar and milk vectors may be of secondary importance. After equilibrium is attained in the soil, standard man might ingest 20 times as much ^{90}Sr by consuming produce from the land irrigated with contaminated water as from consumption of the water. Largely because of foliar contamination, as much as 30 times more ^{137}Cs might be ingested from contaminated crops as from drinking the water. It is not possible to determine the accuracy of these predictions with information currently available. For example, differences in the values used for transfer parameters could significantly change the estimated intake of ^{90}Sr and ^{137}Cs.

At the present time there is little probability of significant quantities of fission products entering man's diet due to irrigation practice. Truck crops in Clinch-Tennessee River environment contribute little to the total quantity of produce and are grown only for a short period during the year. However, crop irrigation with contaminated water could take on greater importance in areas where climatic conditions are more conducive to year-round irrigation of large agricultural plots.

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[29] *Report of the United Nations Scientific Committee on the Effects of Atomic Radiation*, United Nations General Assembly, Official Records: Seventeenth Session, Suppl. 16 (A/5216), pp. 291 and 306, New York, 1962.

[30] *Dietary Evaluation of Food Uses in Households in the United States*, U.S. Department of Agriculture, Household Food Consumption Survey 1955, Report 16, November 1961.

[31] *Estimates and Evaluation of Fallout in the United States from Nuclear Weapons Testing Conducted Through 1962*, Federal Radiation Council, Report 4, 17 (May 1962).

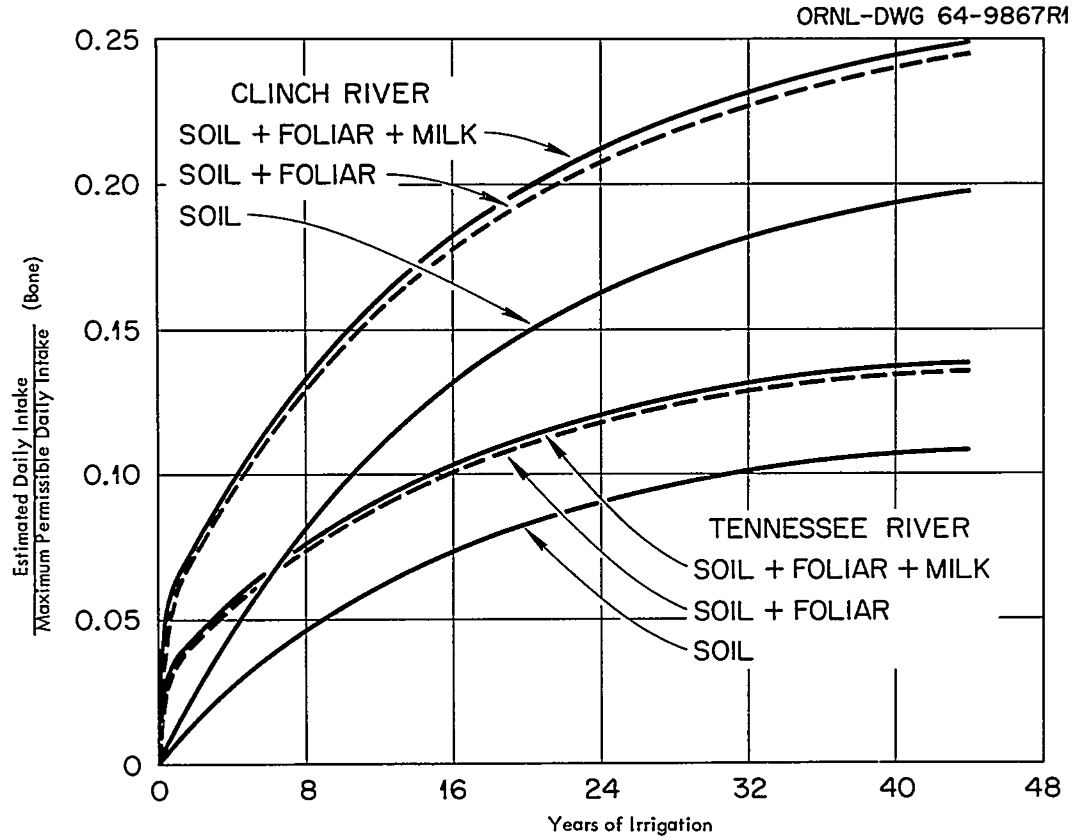

Fig. 7.7. Potential Contribution to MPI by ^{90}Sr in Irrigation Water.

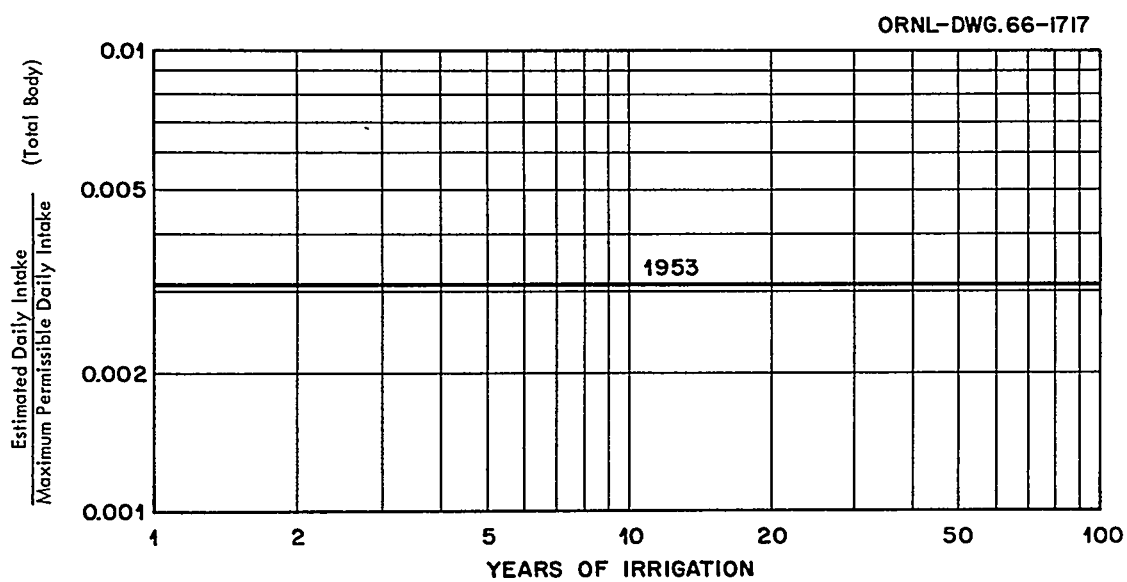

Fig. 7.8. Potential Contribution to MPI by ^{137}Cs in Clinch River Irrigation Water.

8. Conclusions and Recommendations

CONCLUSIONS

Distribution of Radionuclides in River Water[1]

The radionuclides of primary importance in the Clinch River Study were ^{90}Sr, ^{137}Cs, ^{60}Co, and ^{106}Ru. Radiochemical analyses of water samples collected in the sampling network during the period of study indicate the following: (1) that ^{90}Sr, ^{60}Co, and ^{106}Ru in White Oak Creek water, Clinch River water, and Tennessee River water were associated principally with dissolved solids, that is, these radionuclides were either in solution or associated with very fine suspended particles not removed by the supercentrifuge ($<0.7\ \mu$); (2) that ^{137}Cs, in marked contrast to the other radionuclides, was associated with the larger-size suspended solids in White Oak Creek and Clinch River waters; and (3) that 70 to 80% of the ^{137}Cs found in Tennessee River water was in solution or associated with the very fine solids not removed by the supercentrifuge. This finding is probably due to the fact that most of the Clinch River sediment had settled by the time this water reached the sampling stations on the Tennessee River (Watts Bar Dam and Chickamauga Dam).

Distribution of Radioactivity in Bottom Sediments[2]

From information obtained on sediment cores taken from the Clinch River bottom, the following conclusions can be drawn: (1) variations in gross gamma radioactivity with depth largely reflected variations in ^{137}Cs content of the sediment; (2) similarities in the variations with depth of many cores reflected the patterns of annual releases of ^{137}Cs from White Oak Creek; (3) similarities in the vertical distribution of ^{60}Co and ^{137}Cs suggest that incorporation of these radionuclides in the sediment was by deposition of suspended solids entering the river from White Oak Creek; and (4) estimated inventories of radioactivity in Clinch River bottom sediment indicate a relatively small accumulation of contaminated sediment – approximately 200 curies or about 1.5% of the total radioactivity of releases to the river since 1944. The quantities shown in Table 5.4, which have

[1] M. A. Churchill *et al.*, "Concentrations, Total Stream Loads, and Mass Transport of Radionuclides in the Clinch and Tennessee Rivers," *Supplement to Status Report No. 5 on Clinch River Study*, Clinch River Study Steering Committee, ORNL-3721, Suppl. 1 (August 1965).

[2] R. J. Pickering *et al.*, "Radioactivity in Bottom Sediments of the Clinch-Tennessee Rivers," *Proc. Symp. Disposal of Radioactive Wastes into Seas, Oceans, and Surface Waters*, International Atomic Energy Agency, Vienna, Austria, May 16–20, 1966 (in press).

taken account of radioactive decay, represent 21% of the ^{137}Cs, 9% of the ^{60}Co, 0.4% of the ^{106}Ru, and 0.2% of the ^{90}Sr released to the river during nearly 20 years of Laboratory operations.

Over 81% of the identified radioactivity in Clinch River bottom sediment occurs from CRM 16.9 downstream to the river's mouth, in the backwaters of Watts Bar Reservoir. In the upstream, swifter-flowing portion of the study reach, radioactive sediment occurs only along the sides of the stream channel. Maximum concentrations occur near the mouth of White Oak Creek.

Sorptive properties of the sediment are controlled largely by the clay minerals present, which occur primarily in the finest sediment fraction. Results of the desorption tests (Table 5.8) indicate that radionuclides in the sediment would not be released by leaching with river water.

Dispersion and Dilution of Radionuclides Downstream[1]

The work on surface water hydrology was undertaken primarily to define the dispersion and dilution of contaminants in the river system. Tracer tests and other special investigations were made to determine the influence of power releases from Melton Hill Reservoir on the distribution and transport of radionuclides downstream. Since the ebb and flow of water in White Oak Creek embayment due to intermittent discharges from Melton Hill Dam would be much the same as flow in a tidal estuary, it was necessary to develop an understanding of the dispersal of White Oak Creek water into the Clinch. From the data on routine gage-height and discharge measurements, special observations, flume tests, and tracer tests, it was concluded that: (1) the dispersion process due to power releases is not greatly different from that for steady-flow conditions, especially at sections of the stream considerably removed from the outfall of White Oak Creek; (2) the dispersion of White Oak Creek water over the entire cross-sectional area of the Clinch River occurs between CRM 18 and CRM 15; (3) predictions of dispersion in the Clinch based on pulsed releases and a modified tidal estuary analysis agree very well with observed concentrations of dye tracers (Fig. 5.12); (4) the median daily dilution factor for White Oak Creek water in Clinch River water is 570 (ranging from 150 to 1050 at the outfall), being lower in the winter and early spring than in the summer and early fall; and (5) the minimum dilution factors at ORGDP water intake (CRM 14.4), during peak concentrations early in the week after the weekend shutdown of turbines at Melton Hill Dam, are 54 and 17 for summer and winter conditions respectively.

Mass Balance Analysis.[1] — The water sampling and analysis programs were designed for the application of mass balance techniques to develop a clear understanding of radionuclide accumulation and transport downstream. One important compartment in the system, that is, total radionuclide accumulation in Clinch River biomass, was impossible to measure and had to be estimated.[3] As will be seen below, this compartment proved to be insignificant as far as the mass balance was concerned. The results of the analysis (Figs. 5.4–5.7) lead to these conclusions: (1) a large percentage of the ^{90}Sr and essentially all the ^{106}Ru at Oak Ridge (White Oak Dam

[3] F. L. Parker, "Clinch River Studies," in *Transport of Radionuclides in Fresh Water Systems*, TID-7664, pp. 161–91 (July 1963).

and CRM 41.5) passed through the river system to Chattanooga in the water phase; (2) there was a very slight loss of ^{60}Co in the Clinch due to sedimentation, but from there on past Chattanooga the only discernible effect in the river system was that due to dilution; and (3) only an insignificant amount of the total load would be in the biomass at any given time, even under the most conservative assumptions relative to production and uptake. Thus, at least so far as the critical radionuclide ^{90}Sr is concerned, this river system can be thought of as a pipeline.

Radionuclide Uptake and Turnover in Aquatic Organisms

Biological investigations associated with the Clinch River Study included two preliminary surveys, namely, fish tagging and sampling of bottom organisms. Following these familiarization surveys of the diverse biota, certain organisms were selected for intensive study on the basis of their biogeochemical, behavioral, and morphological characteristics. The objective of the more detailed intensive studies was to establish concepts relative to interactions between contaminated water releases and organisms in the Clinch-Tennessee Rivers.

Indicator Organisms. – The study of clams as an indicator organism for ^{90}Sr was one of the first to apply the idea of specific activities to environmental samples.[4] The results, later corroborated by the water sampling and analysis program, showed that ^{90}Sr concentrations in river water hundreds of miles from the point of release (White Oak Dam) could be predicted on the basis of the dilution of contaminated water in noncontaminated water. Subsequent research on the white crappie demonstrated that it was possible to predict ^{90}Sr body burdens in the fish for different waste releases by using specific-activity measurements together with biological half-lives.[5] The white crappie was selected for intensive study because the fish-tagging survey showed that this fish did not migrate over significant distances in the river. Hence, the fish sampled were exposed chronically to radionuclide releases in the Clinch.

Knowledge of the biological half-lives of radionuclides in different fish tissues was used in a study of smallmouth buffalo movements between White Oak Creek embayment and the Clinch River. As expected, radioactive rings persisted in the scales of fish that had lived in White Oak Creek and then had moved out into the river. The finding that only a small proportion of these fish moved from the creek to the river provided important information for the evaluation of radiation safety.

Biological Vectors and Reservoirs. – In accordance with geochemical principles, the reservoir of mineral elements incorporated in the biota at any one time is small. Many radionuclides are concentrated in organisms, but, even in the case of ^{90}Sr in clamshells, the total quantity incorporated in the biomass is small when compared with the quantity in the environment. Similarly, when the activities and habits of aquatic organisms are considered, they are insignificant as vectors of radionuclide dispersal in the environment.

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[4] D. J. Nelson "Clams as Indicators of Strontium-90," *Science* 137, 38–39 (July 6, 1962).

[5] D. J. Nelson, "The Prediction of ^{90}Sr Uptake in Fish Using Data on Specific Activities and Biological Half-Lives," *Proc. Intern. Symp. Radioecological Concentration Processes*, Stockholm, Sweden, April 25–29, 1966 (in press).

Radiation Effects on Aquatic Organisms.[6] – A study of the effects of radioactive water and sediments on a natural population was made tractable by selection of a species having salivary gland chromosomes. The low levels of radioactivity in White Oak Creek embayment were not expected to result in gross damage to the organisms. However, salivary gland chromosomes of *Chironomus tentans* larvae were used for detailed analysis of chromosomal aberrations. Aberrations observed only in the populations exposed to White Oak Creek water and sediment were attributed to ionizing radiation. The newly induced aberrations were eliminated from the population, and the adaptive chromosomal arrangements were not affected. Hence, the survival of this population apparently was not affected by radiation.

Radiation Dose to Downstream Populations[7]

Potential radiation hazards due to ORNL's contaminated waste-water releases to the Clinch River over the past 20 years were evaluated on the basis of conservative estimates of dose equivalents (external and internal) which populations downstream might have received as a result of (1) drinking contaminated water, (2) eating contaminated fish, (3) swimming, skiing, or fishing in contaminated water, (4) being exposed to contaminated sediments on the river bottom, on the river bank, or in a water treatment plant, and (5) eating foodstuffs grown on plots irrigated with contaminated river water. The objectives of this evaluation were to develop a generalized method of safety analysis that might have application to similar problems elsewhere and to establish, as factually as possible, that no undue radiation exposures to downstream users of the river had resulted or would result from disposal to the Clinch River.

Estimates of Cumulative Dose. – Results of the analysis indicate that all population groups (age groups) considered received doses well below those permitted by ICRP, NCRP, and FRC. The estimated total dose to the skeleton of the critical group (18-year-olds) using the Clinch River for 20 years was 3.2 rems. The estimated total dose to the skeleton of the critical group (14-year-olds) residing on the Tennessee River for 20 years was 0.45 rem. In both cases, the dose estimates are less than one-tenth of the permissible. These estimates are believed to be high as a result of the conservative assumptions used in their estimation.

Critical Radionuclides and Exposure Pathways. – Strontium-90 is the most important radionuclide in waste waters released to the Clinch River, contributing more than 99% of the skeleton and total-body dose and 70% of the thyroid dose. As a result of estimated ^{90}Sr intakes, the skeleton is the critical organ, receiving about 5 times the total dose to other organs considered (thyroid, GI tract, and whole body). Of all pathways of exposure considered, the consumption of con-

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[6] D. J. Nelson and B. G. Blaylock, "Preliminary Investigation of Salivary Gland Chromosomes of *Chironomus tentans* Fabr. from the Clinch River," in *Radioecology*, pp. 367-72, Reinhold, New York, 1963.

[7] K. E. Cowser and W. S. Snyder, "Safety Analysis of Radionuclide Release to the Clinch River," *Supplement to Status Report No. 5 on Clinch River Study*, Clinch River Study Steering Committee, ORNL-3721, Suppl. 3, p. 99 (May 1966).

taminated water and contaminated fish was found to be the most important. Looking toward the future, the consumption of foodstuffs grown on irrigated soil could conceivably become the most important pathway of exposure. At the present time, however, there is no irrigation of agricultural land with Clinch River water.

Dose Commitment. – The release of radioactive contamination to a surface stream implies a certain dose commitment to populations using the stream for drinking water, fishing, and recreation, especially if the radionuclides have long effective half-lives. The dose continues to be delivered after the period of intake. Thus, it should be the general practice in such cases to assess upper limits of the dose commitment so that proper account will be taken of it (1) if changes in permissible dose levels should occur, (2) if future installations should wish to release effluents under comparable conditions, or (3) if accidental releases should occur. The estimates of dose commitments for each age group, beginning in 1964 and extending to age 65, showed that the commitments in all cases were well below prescribed limits. Methods developed in this study will be useful in assessing dose commitments for the future.

Long-Term Monitoring in the Clinch River

Considering the results of the Clinch River Study and assuming that local environmental characteristics (river regime, water use, population distribution, and population habits) and radionuclide releases remain essentially unchanged, the Steering Committee reached these conclusions regarding monitoring in the Clinch River: (1) river water is the principal medium for transporting radionuclides and currently is the most important vector for radiation exposure of the general public; (2) bottom sediments provide only a negligible source of dose to man, and the potential hazard due to the accumulated radionuclides is small; (3) consumption of fish flesh in 1960 to 1963 could have caused a dose approximately equal to the ingestion of water; (4) continuation of a dependable monitoring system is encouraged to account for the routine releases of low-level contaminated water and to detect inadvertent releases of larger loads of radioactive materials; and (5) standard techniques for collection and analyses of environmental samples should be followed, and, if more than one laboratory analyzes samples from the river, interlaboratory comparisons should be made to assure that the results will be comparable.

RECOMMENDATIONS

The four subcommittees of the Steering Committee were requested to submit recommendations regarding long-term monitoring in the river system and also regarding further studies that were considered desirable. These recommendations were accepted by the Steering Committee, but not adopted as a formal action, and are summarized in reports of the Clinch River Study in order to make available the considered opinions of the several specialized groups. A brief indication of the subcommittee recommendations is given below.

Water Sampling and Analysis

The recommendations by this subcommittee are available in its final report published as ORNL-3721, Supplement 1 to Status Report No. 5.[1] The subcommittee recommended that continuous monitoring and proportional sampling should be carried out at the point of release (White Oak Dam at present) and that weekly composite samples should be examined for concentrations of the major radioactive constituents. Other data such as stream-flow rates, essential for interpretation of the analytical results, should be collected. The subcommittee also recommended that proportional sampling should be carried out at selected points in the river upstream and downstream from the mouth of White Oak Creek in order to differentiate between radioactive materials from the Laboratory and those from fallout or other sources. Specific recommendations of cross checks and other safeguards to assure accuracy and comparability of data from the analytical laboratories were outlined by the subcommittee.

Bottom Sediment Sampling and Analysis

This subcommittee recommended that monitoring for radionuclides in bottom sediments of the river should be continued as long as radioactive releases can be shown to have a significant influence on the radioactivity of river-bottom sediments. The subcommittee recognized that during the period of the Clinch River Study the potential for human radiation exposure from bottom sediments was small, but it recommended that a moderate program of sediment monitoring should be continued. The subcommittee made specific recommendations regarding locations for sediment monitoring and sampling, measures for assuring that monitoring methods are the most suitable for this purpose, and the frequency of radiation surveys in relation to the time of sediment surveys by the TVA (see ref. 8).

Aquatic Biology

Biological monitoring and further studies of the biological phases were recommended by the Subcommittee on Aquatic Biology as outlined in Status Report No. 6, ORNL-3941.[9] It was the consensus of the subcommittee that annual monitoring of both game fish and commercial food fish should be continued and that fish by-products and biota other than fish should be sampled as a basis for safety evaluation if significant exposure situations should develop. Specific suggestions were made as to the species of fish most suitable for the monitoring program, the number of specimens that should be collected for analysis, and other factors considered important.

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[8] P. H. Carrigan, Jr., *et al.*, "Radioactive Material in Bottom Sediment of Clinch River: Part A, Investigations of Radionuclides in Upper Portions of Sediments," *Supplement No. 2A to Status Report No. 5 on Clinch River Study*, Clinch River Study Steering Committee, ORNL-3721, Suppl. 2A (in press).

[9] R. J. Morton (ed.), *Status Report No. 6 on Clinch River Study*, Clinch River Study Steering Committee, ORNL-3941 (in press).

Safety Evaluation Studies

The final report of this subcommittee was published as ORNL-3721, Supplement 3 to Status Report No. 5 on the Clinch River Study.[7] The subcommittee recommended that monitoring activities should be designed to emphasize current and critical pathways of radiation exposure to man. At present these are consumption of water and fish, but other possibilities should be investigated occasionally and monitored if necessary. One such possibility would be future use of Clinch River and Tennessee River waters for irrigation of food crops.

All of the subcommittees recognized that the investigations authorized under the Clinch River study program had been completed. They believed, however, that there are additional aspects on which further studies would be justified since they may become important in the future. For this reason, further research on particular aspects of contamination in the Clinch River system was recommended by the subcommittees, and these recommendations were endorsed by the Steering Committee.

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